THE PENNSYLVANIA STATE COLLEGE

Mineral Industries Series

FERROUS METALLURGY

Volume II

THE MANUFACTURE AND FABRICATION OF STEEL

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THE PENNSYLVANIA STATE COLLEGE

Mineral Industries Series

Van Winkle · MANUFACTURE OF AVIATION GASOLINE

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VOL. I. INTRODUCTION TO FERROUS METALLURGY

VOL. II. THE MANUFACTURE AND FABRICATION OF STEEL

VOL. III. (*In Preparation*)

MINERAL INDUSTRIES SERIES

The Manufacture and Fabrication of Steel

FERROUS METALLURGY

VOLUME II

by

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THE MANUFACTURE AND FABRICATION OF STEEL

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FOREWORD

The primary mineral industries of the nation are among its greatest sources of revenue. Of its primary mineral industries, the processing of iron ore into pig iron and steel and the fabrication of the resultant products are of primary importance. Since ironworking conditions and steel mill practice are constantly changing, owing to the results of research and experience, it is important that the workers in this industry continue to improve in their efficiency to meet the changed conditions. The best possible way to do this is through study which, when coupled with the practical experience obtained at their place of employment, tends to maintain the workers at their highest efficiency.

This is the second volume of a three-book series prepared by E. J. Teichert, formerly supervisor of Metallurgy Extension of The Pennsylvania State College, and used in connection with a program of training for persons interested in the iron and steel industry. It covers all the common methods of manufacture and processing steel, including its primary fabrication. Every known care has been exercised to present the subject matter in as clear and concise a manner as possible. The extent of the work, however, prevents treating all the subject matter in minute detail. It is believed that the student of this text will obtain a very clear idea of all the processes covered.

In an effort to embody in the text the latest and best information available on plant practice, it was necessary to secure that information where such practice existed. Grateful acknowledgment is hereby extended to the following for their helpful assistance and cooperation in furnishing material included in the text: Air Reduction Sales Company, American Society for Metals, Bethlehem Steel Corporation, Carnegie-Illinois Steel Corporation, Gathmann Engineering Company, Harbison-Walker Refractories Company, Jones and Laughlin Steel Corporation, Mesta Machine Company, John A. Roebling's Sons Company, Surface Combustion Corporation, United Engineering and Foundry Company,

Wellman Engineering Company, Youngstown Sheet and Tube Company, and especially Harry H. Northrup, Republic Steel Corporation, for his help in preparing the section on basic open-hearth steel practice. Acknowledgment has been extended in the text for all material excerpted from current periodicals.

H. B. NORTHRUP, *Director*,
Mineral Industries Extension.

THE PENNSYLVANIA STATE COLLEGE,
December, 1943.

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INTRODUCTION

Schools of mineral industries are concerned with the exploration, development, and conservation of all mineral resources, and with their production, preparation, processing, and utilization. It is natural that Pennsylvania with its long-established prestige of leadership in the production and processing of mineral products should be the first to organize and operate a school of this type in which all branches of instruction and research are united.

The mineral fuels, the metals, and the nonmetallics are nonreplaceable. Their efficient utilization is therefore of the utmost importance in the industrial life of the nation. The interrelated problems concerned with their production and use constitute a distinct division of education. This may be divided into earth sciences, mineral engineering, mineral technology, and mineral economics. The existence of our mineral industries is dependent upon three divisions of service: resident instruction, research, and extension and correspondence instruction.

Ferrous Metallurgy is presented in a series of three texts, which were prepared originally for extension classes in metallurgy covering a three-year curriculum in that subject. They have been maintained up to date by frequent revisions and improvements and have withstood the test of metallurgical critics and teachers for the past ten years, during which time thousands of students have completed the series.

It is recognized that no one text or series of texts can hope to present fully all existing information on ferrous metallurgy. The aim of this series is to present a curriculum in the subject which shall be fundamental in nature, factual in text, sufficiently extensive in scope, and arranged in a manner that experience has found to be most effective in the classroom and in home-study courses.

The Mineral Industries Series, in which these three texts are included, has been developed as a part of The Pennsylvania State College extension service to meet the current economic and

social needs of the nation. There are similar texts in other subjects and advanced, special courses in coal mine mechanization and meteorology. Through this service the principles and truths developed by study and research are translated and carried to the people and applied to the industries. Educational processes taken into the mills, mines, and processing plants result in the promotion of mutual understanding between employers and employees, which is imperative for efficiency, safety, and economy of operation.

EDWARD STEIDLE, *Dean,*
School of Mineral Industries.

THE PENNSYLVANIA STATE COLLEGE,
December, 1943.

FERROUS METALLURGY

VOLUME II

CHAPTER I

THE STEELMAKING PROCESSES

INTRODUCTION

Definition of Steel.—A short, but complete, definition of steel is well-nigh impossible. Before the invention of the Bessemer and open-hearth processes, one had only to distinguish between steel, as made by the cementation or crucible processes, and pig iron, cast iron, malleable iron, and wrought iron. The metallurgy and characteristics of these materials have been covered in Vol. I, and it is necessary to arrive at a definition of steel that will exclude pig iron, cast iron, malleable iron, and wrought iron but will include the product of the crucible process and the more recently developed processes to be discussed in detail in this section.

Steel then, is a ferrous metal containing carbon, cast in an initially malleable mass, usually (but not always) capable of being hardened by quenching, and produced from either pig iron or wrought iron by subjecting them to a refining process which involves complete fusion. This definition immediately excludes pig iron and wrought iron, because it states that steel is made by refining them, pig iron being used in the modern processes and wrought iron in the old crucible process. Also, neither cast iron nor malleable iron is cast in an initially malleable mass, and Armco, or American ingot iron (a product of the open hearth to be discussed later), contains practically no carbon and does not harden appreciably on quenching. This definition is so complicated that its only use is probably in the realm of law when an all-inclusive definition of this type is necessary. For our purpose here, it will be entirely sufficient to remember

that all materials commonly classed as steel are basically iron-carbon alloys.

The rapid strides made by the steel industry in the past thirty years have brought into widespread use a bewildering variety of steels, differing widely in physical properties and chemical composition. The result is that the word "steel" has come to be only a general term, somewhat loosely used, to designate refined ferrous materials of varying carbon contents and, in many cases, widely varying amounts of other alloying elements. The modern methods of making steel will be covered in the following discussion.

Principles of Purification of Pig Iron.—The fundamental commercial method for the purification of pig iron is by oxidation of the impurities, which have a greater affinity for oxygen than has iron, and by subsequent deoxidation of what iron oxide remains in the metal at the end of its purification. The single exception to this is the electric furnace process, in which both oxidation and reduction are integral parts of the method for the removal of impurities. The two commercially available oxidizing agents are air and iron oxide, and the application of each of these requires equipment specially adapted to its use. The method by which air is utilized is called the Bessemer process, and the equipment is so designed that the volume of metal treated is small in order to have uniform penetration of the air through it. When iron oxide is the principal oxidizing agent, as in the open-hearth process, the equipment is designed to give maximum contact between the iron oxide in the slag on top of the metal and the molten metal below it. Hence, the bath has a large surface and is quite shallow in depth. It should be emphasized, however, that both of these oxidizing agents play a part in the purification of pig iron by any method, but that by far the most important agent in each process is as indicated above.

In both of the above processes, the purification may be carried out by oxidation alone, called *acid* processes, or by oxidation in conjunction with strong bases (lime, for example), in which case they are termed *basic* processes. By oxidation alone, only carbon, silicon, and manganese are removed, the phosphorus and sulfur in the pig iron being unaffected. On the other hand, strongly basic slag, in conjunction with oxidation, will remove phosphorus and some of the sulfur in addition to the other impurities.

These considerations result in five principal processes for the purification of pig iron: the acid Bessemer, the basic Bessemer, the acid open-hearth, the basic open-hearth, and the electric furnace. Each of these produces a steel somewhat different from the others in composition and physical characteristics and, with the exception of the electric process, requires a pig iron of particular composition. As will be shown later, the available ores in this country produce pig irons in the blast furnace of such compositions that they are most easily adapted to the acid Bessemer and the basic open-hearth processes. Hence, they are the ones most widely used in this country and are the ones that will be discussed more fully than the others.

CHAPTER II

THE BESSEMER PROCESSES

THE ACID BESSEMER PROCESS

The discovery that air alone, if blown through a bath of molten pig iron, would purify it, is credited to an ironmaster of Eddyville, Ky., by the name of William Kelly. As early as 1847, Kelly had started work on the process, but he did not have sufficient funds to carry his experiments to conclusion. There is some evidence[1] to the effect that news of this discovery reached England through a firm of exporters and that Henry Bessemer came to this country under an assumed name and obtained the idea for the process from Kelly by working for him.

Whether there is any truth in this or not, great credit is due to Bessemer for developing the process. He applied for English patents in 1850 but could not obtain United States patent rights because Kelly was able to establish priority. At first, Bessemer was very successful in making high carbon steels from Swedish pig iron. When the process was tried on English pig irons containing much more phosphorus and less manganese, however, it failed dismally because, after a full blow, the metal was invariably brittle when hot (hot short), and Bessemer was forced to erect his own steel plant in order to save the process.

The commercial success of the process on low carbon steels was assured only when Robert Mushet, a year later, demonstrated that, when manganese, in the form of spiegeleisen, was added to the molten metal after a full blow, it reduced the iron oxide previously formed and rendered the steel sound. This discovery placed the process on a firm basis and its development was rapid from that time on. Alexander Halley, an American, later developed many improvements in the mechanical features of the process.

In this country, the first commercial installation of a converter was put into operation at Wyandotte, Mich., in 1864. The con-

[1] KELLY, WILLIAM C., *Trans. A.S.S.T.*, **3**, 7–8 (1922).

verter was modeled after the one built by Kelly for the Cambria Steel Works in 1857. Mushet's process of deoxidation and recarburization was incorporated in the process. The company later failed, owing to the scarcity of wood for charcoal, the use of which was necessary in the blast furnaces supplying the converter.

The acid Bessemer process remained the leading method for the production of steel in the United States until 1908, when the open-hearth process first produced a greater yearly tonnage. From that time on, the Bessemer process has declined in importance and the open-hearth process has continued to expand. When a comparison is made over a period of years between the tonnage of open-hearth and Bessemer steel produced, a striking trend is shown in which the Bessemer production shows a decided drop, while the open-hearth shows a more drastic increase. In spite of this trend, however, Bessemer production still ranks second over all other steelmaking processes. A number of factors[1] have contributed to this trend, such as availability of scrap, investment costs, and product losses.

The effect of scrap availability becomes evident when consideration is given to the fact that the Bessemer process uses little scrap, 5 to 15 per cent of the total metal charge, while the open-hearth uses ordinarily 50 to 60 per cent. With increased availability of scrap, therefore, the open-hearth process obviously became the favored process.

Since scrap had become widely available and cheap, comparative investment costs became an important factor in the trend toward the open-hearth process. The trend taken is probably the result of the fact that an open hearth using 60 per cent scrap can be built with about 40 per cent of the investment for blast-furnace facilities as compared to the iron requirements for a Bessemer plant, which uses practically 100 per cent pig iron.

The loss of products as manufactured by the Bessemer can be attributed to both metallurgical and mechanical reasons. For example, both rails and heavy structural shapes were lost, owing to its poor reputation for dependability. Then with the development and expansion of such products as seamless pipe, flat-rolled products, and tin plate, as produced on the continuous strip mill, the tonnage demands and the fact that companies

[1] GRAHAM, H. W., The Acid Bessemer Process of 1940, *Metals Tech.*, October, 1940.

having no Bessemer facilities were not interested in such development, the open-hearth process was further favored.

From a metallurgical point of view, the attitude that Bessemer steel is inferior to and less uniform than open-hearth steel has some justification. This view is due to the fact that the Bessemer process has certain elements of variability that contribute to nonuniformity and make control difficult. This is partly due to the lack of chemical and physical control and partly because Bessemer blows are of smaller tonnages than open-hearth melts. Recent investigations on the control of Bessemer blowing and the ultimate product have, however, brought about a very favorable change in the viewpoint regarding quality differences.

It should be pointed out that, in spite of the trend toward open-hearth steels, the Bessemer process has continued to exist because no other process has been developed that produces steels with certain inherent qualities: machinability, which is probably the most important; weldability; stiffness; and sensitivity to cold work.

Bessemer Products and Properties.—The major tonnage of steel produced by the Bessemer process goes into the production of free-cutting screw steels, skelp for butt and lap-welded pipe of smaller sizes, sheet steel, tin plate, galvanized sheets, light structurals, special shapes, low carbon wire, hoops, bolts, nuts, reinforcing bars, and cold-drawn rods and bars.

In the wire mills, Bessemer steel is used where stiffness or rigidity is required for manufacturing barbed wire, steel wool, wire nails, and other products. Tin plate is a large outlet owing to the superior stiffness that makes it particularly applicable in the manufacture of containers. In the production of welded pipe it is outstanding because of its excellent welding and threading properties. Probably its most important use is in the high sulfur grades, known as the Bessemer screw steels, in which its machining performance is practically unequaled. In the production of cold-drawn rods and bar stock, it has an important outlet because of its high sensitivity to cold work as compared to open-hearth grades.

The reason for the superiority of Bessemer steels over the ordinary basic open-hearth steels in the properties just mentioned has not as yet been determined. Several theories may be advanced. The first is the high phosphorus content, which

formerly was considered detrimental but now may be considered as a useful element up to and within certain limits. It is interesting to note, however, that open-hearth steels rephosphorized to the same analysis as Bessemer do not possess Bessemer characteristics. A second theory pertains to the dissimilarity in methods of oxidation. A third is based upon the high nitrogen content which usually ranges between 0.012 and 0.015 per cent as compared with approximately 0.004 per cent of a typical scrap practice in the basic open hearth.

The list shown in Table 1-II is typical of chemical specifications for these various applications. This represents only a selected list.

TABLE 1-II.—BESSEMER CHEMICAL SPECIFICATIONS*

Product	Percentage required			
	Carbon	Manganese	Phosphorus	Sulfur
Screw steel (standard grade)	0.08–0.16	0.60–0.90	0.09–0.13	0.100–0.180
Screw steel (high sulfur grade)	0.08–0.16	0.60–0.90	0.09–0.13	0.200–0.300
Screw steel (high carbon grade)	0.25–0.35	0.60–0.90	0.09–0.13	0.100–0.180
Skelp	0.08 max.	0.30–0.60	0.11 max.	0.08 max.
Bars, track spikes, sheet, and tin plate	0.10 max.	0.30–0.50	0.11 max.	0.07 max.
Soft wire	0.12 max.	0.60 max.	0.11 max.	0.08 max.
Medium wire	0.10–0.20	0.70 max.	0.11 max.	0.08 max.
Reinforcing bars	0.15–0.35	0.70 max.	0.11 max.	0.08 max.
Structural soft	0.07–0.12	0.30–0.60	0.11 max.	0.08 max.
Structural medium	0.25–0.35	0.30–0.60	0.11 max.	0.08 max.
Structural high tensile	0.35–0.45	0.30–0.60	0.11 max.	0.08 max.

* HENNING, C. C., Manufacture and Properties of Bessemer Steel, *Trans. A.I.M.E.*, Iron and Steel Division, **116**, 6 (1935).

The Bessemer Converter.—The converter, as it is used today, is quite different in construction from the early types. It was formerly built as an upright brick-lined steel cylinder, closed at the bottom and converging somewhat at the top to form the nose. The blast was blown in through tuyères at the sides near the bottom and the metal was tapped from a hole in the side of the converter below the tuyères. It was soon found that more even penetration of the blast could be effected if the air was introduced

through the bottom of the converter and also that there was a considerable advantage in being able to pour the heat by tilting the converter.

The size and shape of converter used vary considerably; however, the following description of a 25-ton vessel, as illustrated in

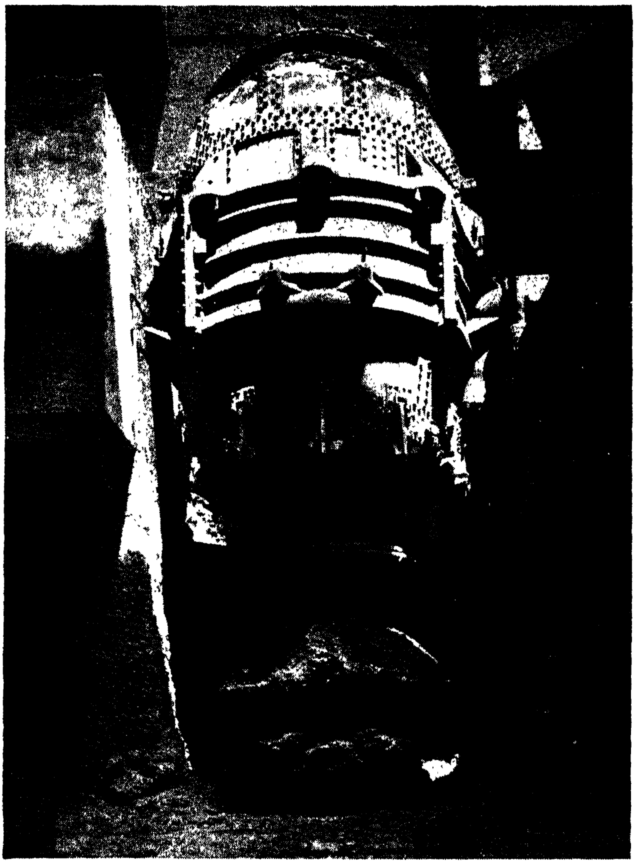


FIG. 1-II.—General view of an eccentric converter. (*Courtesy of Jones & Laughlin Steel Corporation.*)

Figs. 1-II to 3-II, will serve as a representative type. The modern vessel is built in three parts, called the nose, the body, and the bottom. The steel shell is made up of heavy plates riveted together, the nose section being bolted firmly to the body, as is the upper and converging portion of the bottom section.

The bottom proper, however, is keyed to the rest of the shell by means of heavy key bolts in order that it may be easily removed for repairs and a new one substituted. The entire vessel is keyed near the center to a cast trunnion ring which is supported by two heavy trunnions. Each of these trunnions rests on bearings in a framework supported by heavy cast-iron columns. A connection is made between the end of one of the trunnions and the air blast main by means of a packed joint. Between the

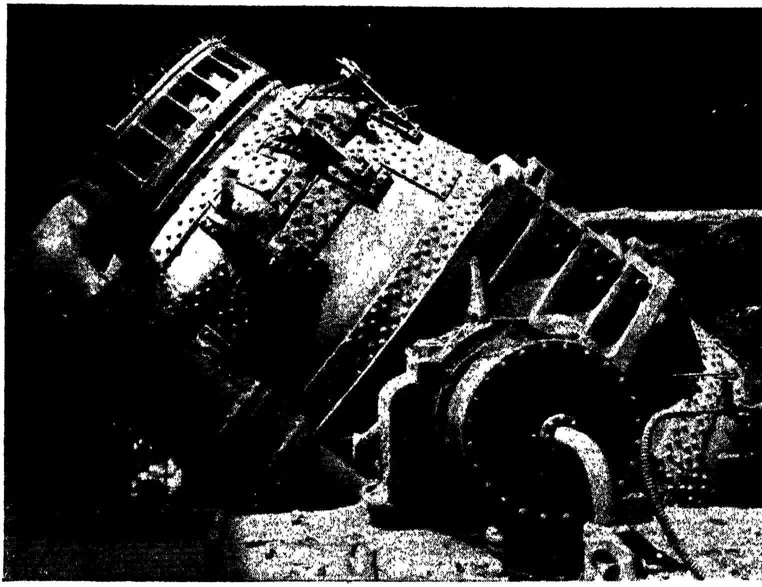


FIG. 2-II.—View of an eccentric converter showing external details of the bottom. (*Courtesy of Jones & Laughlin Steel Corporation.*)

bearing and the vessel, a large pipe leads the air from the trunnion to the wind box in the bottom of the vessel. In this way a continuous connection can be maintained between the stationary blast main and the wind box which must be free to move with the vessel. To the other trunnion is keyed either a rack-and-pinion device actuated by a double-acting hydraulic cylinder, as shown in Fig. 3-II, or a large ring gear connected with a motor-driven mechanism, to revolve the vessel.

The vessel shell is lined to a thickness of 12 to 24 in. with a high-grade siliceous refractory, either a mica-schist rock (firestone) or white sandstone. The application of the refractory

varies. In some cases, mica schist is used in the nose and shoulder, partly because of cost and partly because of its better resistance to erosion, with sandstone in the shaft. The rock lining is set in the shell and held in place by a bonding compound

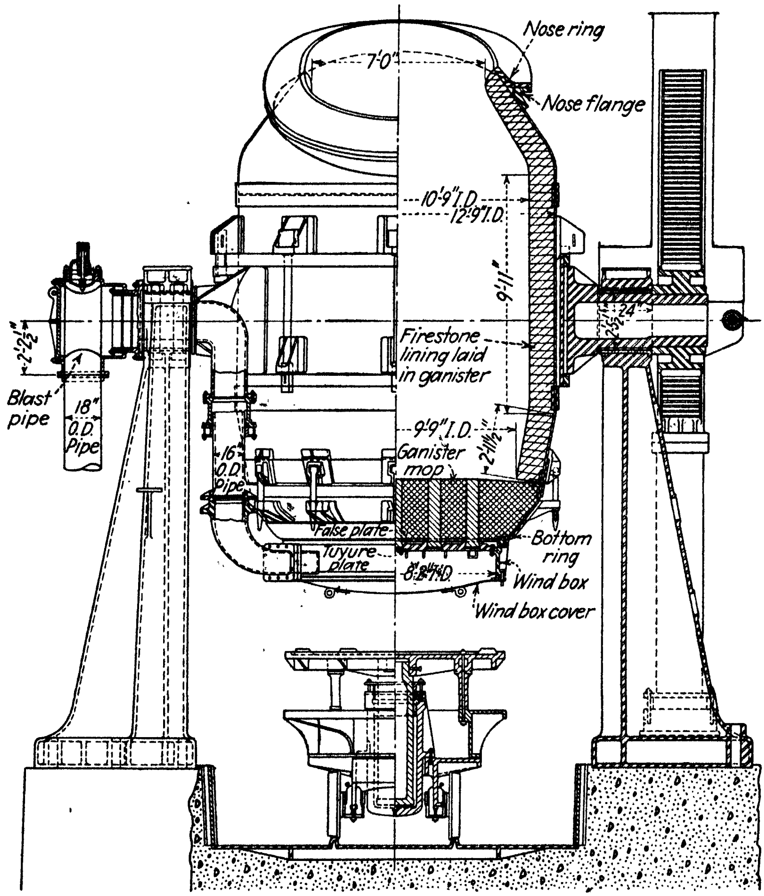


Fig. 3-II.—Sectional elevation of an eccentric converter. (*Courtesy of Jones & Laughlin Steel Corporation.*)

made of high silica ganister rock and a bonding clay ground with water to a plastic consistency. After the lining is completed, it is thoroughly dried and baked by playing gas flames into the body. The lining life will vary in different plants, but a campaign on this part should last from 1,000 to 2,000 heats or blows.

The detachable bottom is rammed against the vessel bottom by means of a hydraulic or electrically operated oil jack mounted in the bottom car. A mud joint is made between the vessel and the bottom to act as a seal. The entire bottom assembly is held in place by means of T-headed key bolts. The bottom consists of the wind box, to which the blast pipe is connected; the wind-box cover, which is held in place by bolts and can be removed independently of the rest of the assembly to inspect the tuyères or blank off any that have been eroded; the side of the wind box, which is a large circular casting about 12 in. deep; the bonnet or shell, which is made of heavy steel plates riveted together in the shape of a bowl with an open bottom; the tuyère plate, which is a heavy steel plate containing sharply beveled openings into which the bottom ends of the tuyères fit tightly; and the false plate or false bottom, which is a heavy steel plate or casting with openings through which the tuyères may be inserted.

The false plate fits into the bonnet and serves to support the material in which the tuyères are packed. From without, this same opening is covered by the tuyère plate, and this in turn is separated from the false plate by means of splice plates that hold the riveted plates together. As a result, an open space of about 1 in. in depth is left between the two plates. Small vents around the outside are connected to this space and serve both as an exit for metal, should there be a break through, and as a warning of a worn-out tuyère. When a tuyère becomes defective or badly eroded, the wind-box cover is removed and the tuyère opening is plugged with a metal disk and clay.

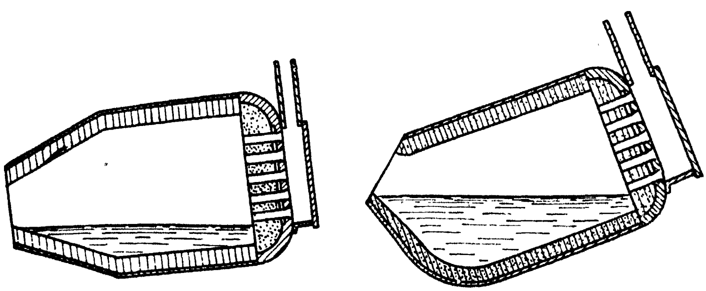
The tuyères, which serve as the connecting medium between the wind box and the interior of the vessel, are inserted through the circular beveled holes in the two plates. Both the number and size of the clay tuyères vary in different plants; they are always arranged, however, in concentric circles in the bottom. The tuyères are cylindrical refractory bricks, flared for a distance of about 6 in. from one end. They range from about 30 to 36 in. in length, 6 to 7 in. in diameter, and are perforated longitudinally by holes whose number depends upon the diameter used.

The tuyères are supported by the tuyère plate and are held in place and reinforced throughout their length with brick tile and mud. The mud, which is a mixture of siliceous ganister and

bonding clay ground with water, is either poured or rammed in place. The water is driven out by heating the entire assembly in a gas-fired oven.

The bottom of the converter is subjected to the most severe wear because of the fact that the air blast coming from the tuyères produces a high local concentration of iron oxide which attacks the tuyère blocks very rapidly. As a result, the bottom life usually averages between 30 and 40 heats before it must be replaced.

The two principal types of converters in use today are called the eccentric and the concentric (Fig. 4-II). Both of these are bottom-blown types; the only side-blown type of converter used



Concentric *Eccentric*

Fig. 4-II.—Comparison of concentric and eccentric Bessemer converters. (*After Rosenholtz.*)

at the present time is the small Tropenas converter used in steel foundry work. The eccentric converter is so called because its mouth is set at an angle and to one side of the vertical axis of the shell. In the concentric type, the mouth is in a plane parallel to and concentric with the bottom of the converter.

Since it is imperative to keep molten metal from running down into the tuyères, the converter should be charged while it is on its side. The capacity is rated as the amount of molten metal that the converter will hold when in charging position, without clogging the tuyères. Figure 4-II shows the relative abilities of the two types of converters to hold the molten pig iron. It is obvious that the advantage in this respect lies with the eccentric type. The eccentric converter has the further advantages of allowing less heat to escape from the nose and of permitting the blast to be shut off more quickly on turning the converter down. The concentric type can be charged or poured from either side,

while in the eccentric type both operations must be done from the belly side. In the concentric type, the area enclosing the tuyère blocks is oval in shape and the short axis of this oval is so placed that a greater volume of metal can be contained in the charging position than if a circular form were used. The capacities of the present-day converters vary from 10 to about 30 tons, a good average being 20 tons.

The Bessemer Plant.—The Bessemer plant is designed conveniently to transport and charge the raw materials required by the converter: molten pig iron, steel scrap, and air. Provision must also be made for preparing the recarburizer, recarburizing the heat, and teeming it into the ingot molds. Last, but not least, a separate division is required to keep the converter bottoms and linings repaired. The design of the equipment to carry out these operations, as well as the actual placement of the various items of equipment relative to the converter, varies so widely from one plant to another, that only a general idea can be attempted.

The converters are usually placed side by side along one wall of the converter house. Each vessel is supported far enough off the ground floor to allow a small car to be run under the converter when it is in an upright position. This car runs on a track and is used in the removal and replacement of the converter bottom. The charging floor of the house is placed just below or at the level of the converter trunnions, and from it all molten materials are charged. A top floor may or may not be provided for the introduction of scrap and other solid materials. Sometimes, the scrap is introduced directly into the scrap chute from a crane, but otherwise a floor is provided at some distance above the nose of the converter when it is in an upright position.

The molten pig iron is brought from the blast-furnace plant in ladle cars and poured into a mixer. The mixer is a large, refractory-lined, cylindrical steel vessel (Fig. 5-II), mounted horizontally on rollers or trunnions so that the metal can be poured from a spout in its center by merely tilting the mixer. The present-day tendency is to construct them in large sizes, 1,000 to 1,300 tons capacity being common. In the modern steel plant, a group of mixers supply both the converter plant and the open-hearth plant with pig iron and are placed conveniently with respect to both of them. One mixer is usually reserved for Bessemer pig iron.

The mixer is indispensable to the steel plant operating under modern methods. Its chief function is to furnish storage space for the molten pig iron and thus make the operation of the steel-making processes independent of the time intervals between casts from the blast furnaces. Thus, a minor breakdown or delay either at the blast furnaces or in the steel plant will not necessitate the closing down of the other. Since it has already been seen that the composition of the pig iron from a blast furnace is hard

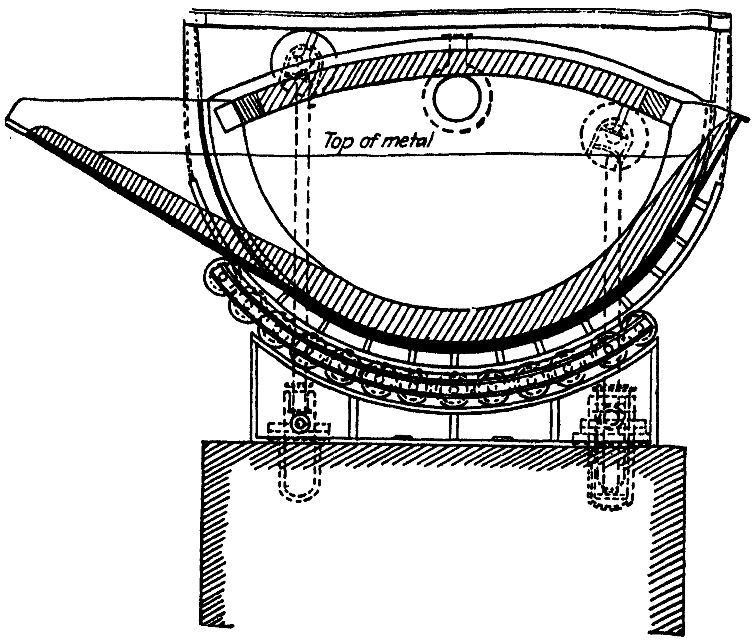


Fig. 5-II.—Cross section of a mixer. (*After Stoughton.*)

to control within narrow limits, the mixer furnishes a means of equalizing the composition of casts from several furnaces. Also, the metallurgist is able to bring the composition of the pig in the mixer to almost any desired composition by melting special mixtures in cupolas and pouring the resultant melts into the mixer. Another big advantage of the mixer is that it will keep its contents molten for an indefinite length of time, since it is so large and since fresh hot metal is being added at frequent intervals. Oil or gas burners are provided to help keep the metal at the required temperature but they are rarely needed under

ordinary conditions. Finally, the mixer removes a small amount of sulfur from the metal because the manganese in the pig iron slowly reacts with FeS, and the MnS produced, not being very soluble in iron, and rises into the slag.

When a batch of metal is needed for a converter blow, the mixer is tilted and the metal poured into a ladle car which is placed on the weighing platform of a large scale and the metal weighed. This car is taken to the converter and its contents poured in. Selected scrap, usually sheared ends of blooms from the rolling mill, is charged into the vessel through the scrap chute while it is blowing. The Bessemer process is not a big scrap user, as less than 10 per cent of the charge is scrap in most cases.

The air blast is supplied to the converter at about 20 to 30 lb. pressure by means of turbocompressors usually located in a separate building just outside the converter house. Some of the older installations still use cylinder blowing engines, but, as in the blast-furnace plant, the trend is toward the use of the smaller and more economical turbocompressors. The blast main runs from the blower house to a manifold near the converters, where the blast is distributed through separate lines to each converter. Both the blast main and the distributing lines are equipped with valves operated by remote control. In some installations, a separate compressor and blast main are provided for each converter, thus simplifying the arrangement.

The teeming ladle into which the heat is poured is taken to the teeming platform by means of either jib or traveling electric cranes. The ladle is a large, refractory-lined steel vessel, shaped like a cup, and equipped with trunnions on either side, by which the crane supports it. Since it is necessary to keep the slag that floats on top of the steel from getting into the ingots, the ladle cannot be tipped and the metal poured over the lip into the mold, but must be poured from the bottom or "teemed" (Fig. 6-II). Consequently, the shell has a hole in the bottom close to the rim in which is inserted a refractory nozzle made of clay, graphite clay, or magnesia, and a stopper of a graphite-clay mixture fits into the nozzle. The stopper is held on a steel stopper rod which extends vertically through the bath of metal and must, therefore, be protected by clay sleeves. The top of the rod protruding from the ladle is fastened to a gooseneck which extends down over

the side of the ladle. A lever mechanism connects this gooseneck to a long rod, an up-and-down movement of which will control the stopper action. The refractory lining of the ladle and particularly the stopper and nozzle deteriorate rapidly owing to the action of the molten steel and must be constantly repaired. The ladle is usually heated before the metal is tapped into it.

The ingot molds into which the steel is teemed from the ladle are made of cast iron and are of various sizes and shapes. In cross section, they may be square or rectangular with rounded

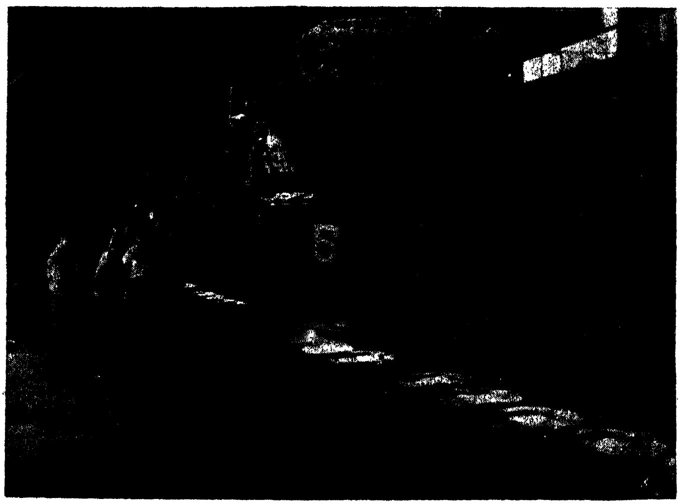


FIG. 6-II.—Teeming the heat. (*Courtesy of Jones & Laughlin Steel Corporation.*)

edges, circular with the walls corrugated, eight-sided, fluted, or twelve-sided. In longitudinal section, they are of two general types. The older, called the "big-end-down" type, is slightly larger at the bottom than at the top, is open at both ends, and when ready for use is mounted on a heavy plate of cast iron called a "stool," which forms the bottom of the mold. The newer type, called "big-end-up," is slightly larger at the top than at the bottom and is either open at the bottom or bowl-shaped and closed except for a round hole which is fitted with a tapered plug that extends through a hole in the stool upon which the mold sets. The taper in both cases is less than ¼ in. per ft. The latter type is often fitted with a removable refractory collar, called a "hot

top," which is placed on top of the mold and slows down the rate of solidification in the upper portion of the ingot. Sketches of representative examples of both the big-end-up and the big-end-down types are shown in Fig. 7-II. The relative advantages of these types of molds will be discussed later.

The last important department of the Bessemer plant to be taken up is the bottom house, usually located just back of the converters themselves. In this department all repairs on the converter bottoms are made and the refractory cements are made

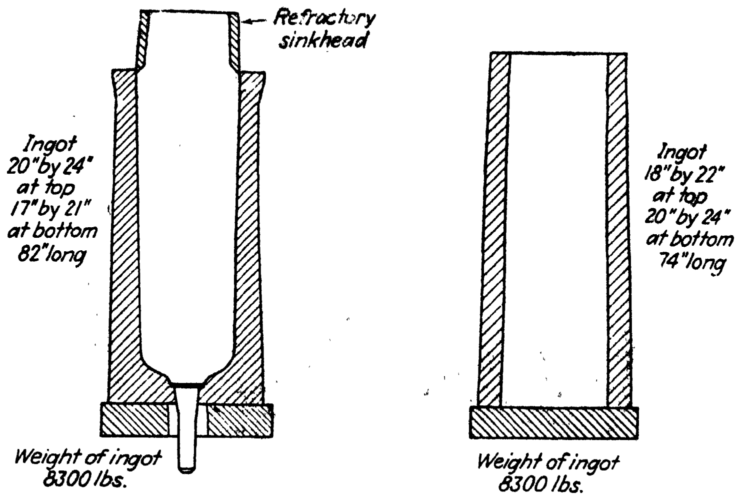


FIG. 7-II.—Big-end-up and big-end-down ingot molds.

up. A converter bottom is removed from the shell by running a small car, equipped with a powerful jack, under the converter bottom (the converter being upright), raising the jack firmly against the bottom, knocking out the key bolts that hold the bottom to the shell, and lowering the jack until the bottom rests on the car. A new bottom is immediately put on the converter by reversing this procedure and the old bottom is taken to the bottom house where the necessary repairs are made. Since the mortar holding the tuyères in place is put in when wet, it is necessary to dry the repaired bottoms carefully and then bake them. For this purpose, a set of ovens, usually gas fired, are provided in which the bottoms receive about a 48-hr. treatment before they are ready to be used again.

Some distance above the charging floor and advantageously placed with regard to the converter, a platform, called the "pulpit," is provided for the blower. From this pulpit, the blower controls the progress of the blow, and all the operations connected with producing the heat of steel are under his jurisdiction. The pulpit is provided with gauges showing the volume of air flowing to the converter per minute, the pressure of the blast, and its velocity. The blower is also able to control the operation of the compressors and the movement of the converter from his position in the pulpit.

Bessemer Iron.—The composition of the pig charged into the converter is of utmost importance to the success of the process. The only heat generated during the blowing operation is that derived from the oxidation of impurities, and this heat must offset the cooling effects due to radiation from the walls of the vessel and from the mouth, and the cooling action of the cold air blown into the bottom. If a new lining is being put into service (even when the lining is heated to a red heat before charging, as is usually done) or a new bottom has just been installed, the chance of the heat's being cold is rather great. Extra care should be taken to have the heat-forming elements in the pig as high as possible.

Silicon and Manganese Content.—As will be shown later, the oxidation of silicon is the chief heat-producing reaction in the converter. For that reason, the silicon content of the pig should be held as closely to a constant value in the mixer as possible. The exact value will differ from plant to plant with small variations in operating practice, but it is nearly always between 1.00 and 1.80 per cent. The total carbon does not vary much in Bessemer pig, usually being between 3.80 and 4.25 per cent. The manganese is usually under 0.60 per cent. The middle of the range in silicon and manganese will give an iron of roughly a 2.5:1 ratio which offers ease of temperature control, produces the proper amount and viscosity of slag, and does not excessively affect the vessel lining. With increasing manganese above the recommended range, there will be considerable loss of metal due to slopping; the slag will be difficult to hold in the vessel while the metal is being poured; and the ladle reaction will be inefficient. With a high silicon content a hot blow will be produced, the temperature will be difficult to control, and the blow

will frequently be accompanied by slopping due to the large amount of superheated slag. With low silicon, a cold blow will result and will be accompanied by an erosive slag due to the higher iron oxide content usually present under these conditions.

Phosphorus and Sulfur Content.—The phosphorus and sulfur in the pig iron go through the Bessemer process unchanged and are present in the finished steel in slightly higher percentages than in the pig iron charged to the converter. The reason for this is that the operation of the process always results in some loss of iron by oxidation or ejection from the mouth and since the phosphorus and sulfur remain unchanged, the percentages of these two elements are higher in the finished product. The maximum allowable percentage of phosphorus tolerated in most specifications for Bessemer steel is 0.100 per cent, although 0.115 per cent is allowed in some cases. The reason for this specification is that phosphorus is believed to be one cause of brittleness in steel and it is, therefore, kept as low as possible. Hence the phosphorus content in the pig iron must be kept far enough below the specification so that the finished steel will not contain more than the foregoing values. The usual percentage in the pig ranges from 0.085 to 0.100 per cent. For the same reasons, the sulfur content in the pig ranges from about 0.03 to 0.08 per cent, the average value being at about 0.05 per cent.

The foregoing specifications account for the division of iron ores into Bessemer and non-Bessemer ores, since the blast furnace will not remove the phosphorus. An iron ore is usually classed as Bessemer if the iron content of the ore is more than 1,000 times the phosphorus content. These ores are scarce and therefore high in price and consequently handicap widespread use of the acid Bessemer process in the United States.

Iron Temperature.—It has been found that, if the iron temperature as it is charged is maintained uniformly between 2200 and 2350°F., smoother converter operation will result.

Bessemer Process.—The operation of the Bessemer process consists essentially in charging the converter with molten pig iron of a particular composition and blowing air through the charge until the silicon, manganese, and carbon are oxidized in the order named. The heat is then deoxidized and additions are made to meet specifications as it is being poured into the teeming ladle. After the heat is held in the ladle for a short

while, it is teemed into the ingot molds. The details of the operation will be discussed in the following paragraphs.

As the blower knows the specifications for the finished steel and the composition of the pig in the mixer, the charge is calculated and the correct amount of pig ordered. The molten pig is poured from the mixer, weighed, and transported to the charging floor of the converter house. The converter is turned down to the horizontal position and the molten pig is slowly poured into it, care being taken to prevent the metal from flowing into the tuyères. The blast is then started and the converter turned upright, the pressure of the air preventing the molten iron from flowing down into the tuyères.

The pressure of the blast forces the air through the molten iron in a fine spray of small bubbles, and chemical reaction between the oxygen in the air and the component elements of the pig iron starts immediately.

The refining process can be easily followed by referring to Table 2-II.

TABLE 2-II.—REMOVAL OF METALLOIDS*

Element	Initial charge, per cent	Metalloid content with increasing blowing time, per cent — Blowing time				
		2 min.	3 min. 30 sec.	6 min.	8 min. 10 sec.	10 min.
Carbon	4.30	3.90	3.75	2.10	0.60	0.03
Silicon	1.25	0.70	0.38	0.30	0.03	0.005
Manganese	0.40	0.10	0.40	0.03	0.01	0.01
Phosphorus	0.085	0.088	0.090	0.092	0.094	0.096
Sulfur	0.035	0.035	0.036	0.037	0.038	0.039

* HENNING, C. C., Manufacture and Properties of Bessemer Steel, *Trans. A.I.M.E.*, Iron and Steel Division, **116**, 137–158 (1935).

The oxygen of the air entering through the tuyères immediately combines with the iron to form iron oxide. This iron oxide, being soluble, is distributed throughout the molten bath by the violent agitation and rapidly reacts with the silicon first and then with the manganese. The oxides of these elements then combine to form a slag. All these reactions are exothermic and

furnish the only heat during the blow. While the silicon and manganese are being oxidized, there is very little reduction of the carbon but, as their removal nears completion, the increased temperature brings about its rapid oxidation. Phosphorus and sulfur in the metal are not removed because of the acid slag; however, the amounts of these elements in the finished blow will be increased slightly as a result of weight loss in blowing.

When the carbon has dropped to the desired percentage, the converter is turned down and the blast is shut off. The metal is then deoxidized and brought to the specified analysis as it is poured into the teeming ladle by making additions of the proper elements, such as manganese, carbon, copper, and sulfur.

The success of the process depends on the skill and judgment of the blower in charge of the converter, and it should be emphasized that he should be competent, have long experience, and be capable of quick and accurate judgment in order to perform his duties successfully. In the operation of the process his most important duties are (1) to control the temperature of the metal in the converter so that it will be at a definite point at the end of the blow to allow sufficient time for recarburization and teeming. (2) He must be able to determine the end point of the blow accurately in order to turn the vessel down and stop the chemical reactions.

The blower has several methods available for controlling the temperature of the iron, once it is poured into the vessel. It is seldom necessary to utilize methods of raising the temperature of the bath since there is generally sufficient heat in the iron as it comes from the mixer. If it is necessary, he can make additions of ferrosilicon, the oxidation of the silicon being the source of heat in this case, or he may "side-blow." Side blowing consists in tilting the converter enough to expose a few tuyère holes and cause a portion of the air to rush over the surface of the metal. The rapid oxidation of iron together with the oxidation of carbon monoxide to carbon dioxide causes a limited increase in temperature. Both these practices are expensive and should be avoided.

In reducing the temperature, the blower may follow one of several practices. During the early part of the blow it is important that the temperature be held sufficiently low to enable the silicon to be removed before the carbon. Otherwise, the high

temperature would bring about oxidation of the carbon and leave an enbrittling silicon residue. To bring about such a control, he will introduce a given amount of steel scrap by means of the scrap chute as soon as the vessel reaches the vertical position. The amount of scrap added to the vessel is estimated from the calculated mixer analysis of the iron, particularly the silicon content. According to experience, then, the heat required to melt the scrap lowers the temperature by the proper amount and compensates for the variation in heat-producing constituents.

Steam is also used as a coolant and is most frequently used as a means of bringing about final adjustments to the finishing temperature. The use of steam has been looked upon as harmful because of hydrogen absorption by the liquid metal but, since there are so many possible variables, the case against its use has not been clearly established.

Iron ore may also be used as a cooling agent. The effect of such addition is to decrease the loss of iron through oxidation, increase the amount of slag, and, by helping to oxidize the silicon, shorten the blowing time as much as 20 to 30 per cent.

To determine the temperature and control the progress of the blow, the blower has in the past relied entirely upon a series of mental and optical standards based on the characteristics of the flame and carbon sparks ejected from the mouth of the converter. A new method[1] has recently been developed whereby his visual estimations can be checked by an instrumentally obtained record which in effect brings about a high degree of uniformity from blow to blow. The instrument, which consists of a suitable photocell and amplifier arrangement, is focused on the flame and produces a continuous graphic record of the progress of the blow. Figure 8-II is a typical chart from such an installation and shows the amount of luminous energy emanating from the flame throughout the blow. The following discussion will serve to correlate the flame characteristics as observed by the blower with the information shown on the photocell chart.

As the vessel is first turned up, a shower of sparks flies from the mouth of the converter followed by a stream of dense brown fumes. These fumes give way almost immediately to a dull-red, short, pointed flame through which building columns or other

[1] "Bessemer Flame Control," Jones and Laughlin Steel Corporation, patented 1939.

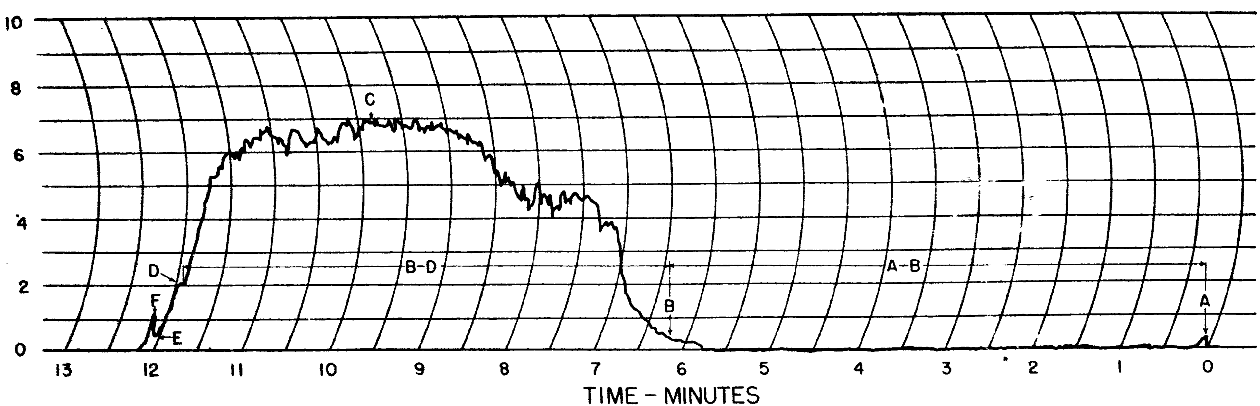


FIG. 8-II.—Chart from photocell installation registering intensity of Bessemer flame. *A*, vessel turned up (start of blow); *B*, end of silicon oxidation and beginning of carbon oxidation; *C*, maximum intensity of flame; *D*, first or high carbon-end point; *E*, vessel turned down (end of blow); *F*, flash back.

A-B represents the silicon phase of the blow; *B-D* represents the carbon phase of the blow.

Height of *C* above the zero line is a relative indication of temperature. (*After D. R. Loughrey, Iron and Steel Engineer*, 1942.)

objects may readily be seen, indicating that the silicon and some of the manganese are being burned out. During this so-called "silicon phase" of the blow, which lasts for approximately 5 to 6 min. and is represented on the photocell chart by *A-B*, several indications may be had regarding the silicon content of the iron. If the sparks issuing from the converter during this interval are large and travel far before bursting into a bloom or blossom, the silicon is high and the iron is hot, while, if the sparks are lifeless and break close to the converter, the silicon is low. As the silicon is reduced in the normal blow, the sparks lose their velocity and keep breaking closer and closer to the mouth of the vessel.

Another indication of the silicon content of the iron may be had by observing the length of time elapsing before the flame becomes opaque. On the photocell chart this point is indicated by an appreciable rise of the curve above the base line, as at *B*.

The point *B* on the chart indicates the point at which the carbon starts to be oxidized. The short flame, which has become luminous, gradually increases in length and brilliancy until it is yellowish white in color. This is due to the increased evolution of CO within the vessel which immediately burns to CO_2 upon coming in contact with the outside air.

The temperature regulation, as has been previously pointed out, is brought about by additions of scrap and steam. Temperature control is still dependent upon the blower's mental standards, established by long experience, regarding certain characteristics which he is able to observe in the flame after adding the scrap or injecting the steam.

If the photocell is used, the height to which the pen rises on the chart may be used as a temperature indication (point *C*). This, however, is not a direct reading but only relative, since consideration must be given to the blast pressure and the number of blanked tuyères.

The temperature regulation should be made so that the correct temperature is attained by the time the carbon content reaches about 1.80 per cent. This is the transition point where iron is changed to steel and is easily detected in the flame. As this point is approached, the typical effervescing iron spark is replaced by a solid spark, until, as the critical is passed, the iron spark completely disappears.

As the carbon content diminishes, the long, brilliant flame starts to shorten rapidly, indicating the approaching end point of the blow. On the photocell chart this point is indicated by the rapid drop of the curve toward the base line. The vessel at this point is moved to a position where all the sparks will fall in a curving arc toward the "turndown" position. The flame at this time is decreasing rapidly in length and is turning to a dark brown with heavy white streaks of carbon flame running through it. This is probably caused by the increased oxidation of the iron in combination with the last carbon. The point at which this change takes place is indicated by a brief pause in the drop of flame luminosity and is called the first or "high carbon" end point. This point, which occurs at about 0.15 per cent carbon, is indicated on the photocell chart at point *D*. Immediately following this change, the major carbon lines disappear from the flame and the sparks fall in straight lines directly in front of the converter, indicating the point at which the vessel should be immediately turned down. On the chart this is indicated by the rapid drop in flame intensity to point *E* where, at about 0.04 per cent carbon, there occurs a slight retardation in the rate of decrease of flame energy. This point has been designated as the end point of the Bessemer blow. As the vessel is turned upon its side, a point is reached where the metal bath drops below the bottom of the tuyères and the flame impinges upon the shield in front of the converter and produces a "flash back" which registers on the chart at point *F*. This is the end of all normal blowing.

The period of time between the end point *E* and the time that blowing has ceased has been called the "afterblow." This afterblow is used as a measure of the degree of metal oxidation and has been found to be an important factor in the control of the particular grade of steel being made. The terms "young" and "full" are frequently referred to in reference to the length of afterblow and, hence, the degree of oxidation of the metal. "Young" indicates that the vessel was turned down shortly after the end point, while "full" indicates that the blow was carried farther along. The timing of the afterblow[1] for a particular grade of steel is based on an experimentally predetermined

[1] Work, H. K., Photocell Control for Bessemer Steelmaking, *Trans. A.I.M.E.*, **145**, 132–150 (1941).

number of seconds between point E and the point at which the vessel is turned down. With certain correction factors based on the number of tuyères blanked, the silicon in the iron, and the weight of the charge, a high degree of uniformity has been obtained. The number of tuyères will affect the air flow; the silicon apparently affects the flame luminosity; and the effect of the charge size is based on the fact that less oxygen is required to blow a small charge than a large one. This would affect the afterblow proportionately.

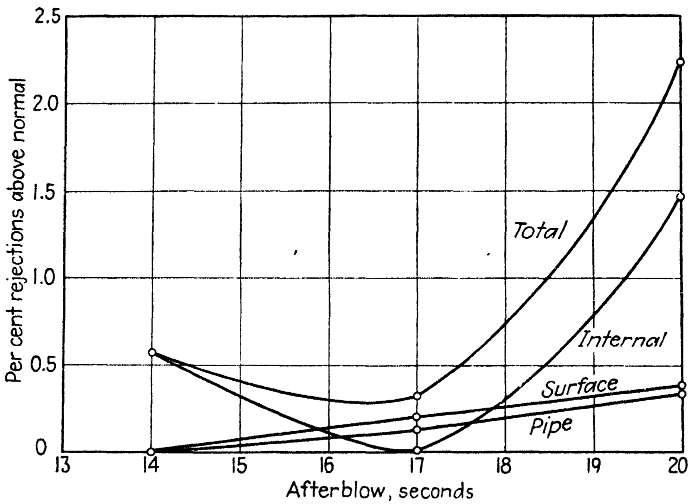


FIG. 9-II.—Rejections of Bessemer steel related to time of afterblow. (*From Work, H. K., "Photocell Control for Bessemer Steel Making," Bull. Am. Inst. Mining Engrs.*, **145**, 1941.)

The effect of the length of the afterblow in relation to etch-test rejections, pipe, surface quality, and total rejection for screw stock steel is shown in Fig. 9-II. The importance of oxidation control in the production of various types of Bessemer steel such as mechanically capped, rimmed, screw steel, and killed and recarburized, as it relates to pouring practice, surface, and interior quality,[1] will be further emphasized in the detailed study of the steel ingot.

The entire length of the blow generally requires from 11 to 18 min., depending upon the weight of the charge, the silicon con-

[1] BOWMAN, H. T., Significance of the Bessemer End Point, *Metals Tech.*. February, 1942, pp. 3–13.

tent of the iron, and the air flow (pressure and tuyères blanked). The blown metal contains only traces of silicon and manganese and from 0.03 to 0.05 per cent of carbon. The phosphorus and sulfur increase proportionately owing to the oxidation of other metalloids, to the iron that is contained in the slag, and to the material ejected and volatilized. The loss ranges from about 8 to 10 per cent of the charged weight, giving a converter yield of from 90 to 92 per cent.

Deoxidation and Recarburization.—Immediately following the blow, the metal is poured from the converter into a teeming ladle, care being taken to retain as much of the slag in the converter as possible. During and after this action, the metal is deoxidized and recarburized to bring about, (1) control of the carbon content, (2) deoxidation of the metal, (3) addition of such elements as copper, sulfur, and manganese, to meet metal specifications. The additions may be made in a number of ways such as all added in the ladle, some in the ladle and some in the mold, some in the converter, or some in all three.

Depending upon the type of steel specified, different types of deoxidizers and recarburizers are used as well as the procedures to be followed in deoxidizing and recarburizing. The most commonly used deoxidizers and recarburizers are ferromanganese, spiegel, ferrosilicon, molten iron, and crushed anthracite coal or coke dust. The analyses for the above-mentioned ferroalloys may be found by referring to pages 69 and 70.

Since the Bessemer tonnage produced consists largely of low carbon grades (carbon under 0.20 per cent), very little recarburization is done except that which is accomplished through the addition of ferromanganese. The practice followed in making this addition varies, but all operators make the addition to the ladle. In some plants it is heated to from 1000 to 1500°F.; in others, it is wetted so that the steam generated when it makes contact with the molten slag will blow the slag away and thus minimize the possibility of its entrapment with the slag; in others, it is screened to a maximum size of 1½ in. and then added. In the past, experience has been the guide used to determine the anticipated loss or efficiency of the addition, and this depended not only upon the percentage of manganese to be added but also upon whether the blow was finished "full" or "young." In the case of a manganese specification of under

0.60, with a full blow the loss would be about 20 per cent, while if blown young, about 15 per cent. When the photocell chart is used, a relationship can be established between the length of afterblow and the efficiency of the manganese addition. It has been found[1] that the manganese efficiency is inversely proportional to the percentage of FeO in the metal and, since the length of afterblow is a primary factor in the control of FeO in the metal, a relationship should exist between it and the efficiency. Research has shown that a relationship does exist and the manganese efficiency is inversely proportional to the length of the afterblow, *i.e.*, a short afterblow will give high efficiency, while a long afterblow will give low efficiency.

For higher carbon specifications (carbon over 0.15 per cent), the carbon may be caught as it is coming down, but this is difficult and not usually practiced. The most dependable practice in recarburizing is by adding molten iron in the ladle. This seems to be preferred to the use of crushed anthracite or coke dust. Spiegel or high carbon ferromanganese is also used to meet the manganese and aid in meeting the carbon specifications.

With such additions as copper to produce steels resistant to atmospheric corrosion and sulfur to produce screw stock steels, it is the practice to add these elements directly to the converter. The sulfur may be added as iron pyrites or as flowers of sulfur, the forming giving the better results. It may also be added to the ladle as flowers of sulfur or as ferrous sulfate.

Mold additions to bring about deoxidation or semikilling is practiced using shot aluminum or fine 50 per cent ferrosilicon.

The deoxidation of the heat takes some time, since the oxides produced by the reaction must be given time to rise through the bath and join the thin slag blanket that protects the metal from oxidation during the holding period. For this reason and also to allow for unforeseen delays, the metal is usually tapped from the converter at a considerably higher temperature than the desired teeming temperature and the heat held until it cools to the required temperature. In usual practice, the heat is held in the ladle for at least 10 min. before teeming.

Teeming.—The teeming of the heat is of utmost importance in the production of good steel. The temperature of the steel during teeming, the rate of flow of metal into the mold, the type

[1] BOWMAN, H. T., *op. cit.*

of mold, mold coatings, and preparation, and the method of filling the mold are all important factors in the making of an ingot suitable for fabrication.

The control of teeming temperature is an important factor in quality control of Bessemer steels. Extreme temperature variations are to be avoided, since with low temperatures, heavy skulls, difficult pouring, and scabby, dirty ingots will result. Hot heats, depending upon the grade produced, will develop undesirable surface conditions on the semifinished product as a result of poor mold action; bring about production difficulties, such as sticker ingots; and adversely affect the refractories of the vessel and ladle. Studies on the effect of teeming temperature on surface quality[1] have shown that the optimum temperatures for different grades of steel are as follows: capped steel 2875 to 2900°F., rimmed steel 2845 to 2875°F., and screw steel 2860 to 2890°F.

The rate of metal flow in teeming is controlled by the size of the nozzle. It has been found[2] that sizes ranging from 1¾ to 2⅛ in. seem to be good all-purpose sizes on the majority of Bessemer grades and will produce good quality steels with little difficulty from skulls.

The size and design of the molds used in the production of Bessemer steels are as a rule the same as those used in open-hearth steel, namely, open top big-end-down, big-end-up, and bottle top big-end-down. Detailed discussion of these types may be found in Chap. VII.

The same precautions regarding mold coatings and mold temperature for Bessemer steels apply exactly to the practices used in open-hearth steels. The practice regarding mold temperature varies somewhat, but a temperature of between 200 to 400°F. is considered satisfactory. With normal operating conditions, the mold rotations can be so scheduled that they will be at correct temperature and ready for reuse about every 12 hr.

The primary purpose of mold coatings is to protect the mold and improve the ingot surface by preventing splashing steel from sticking to the mold wall and causing scabs on the ingot. For

[1] McGinley and Woodworth, A Study of Modern Bessemer Steels, *Trans. A.I.M.E.*, **145**, 151–159 (1941).

[2] Henning, C. C., Manufacture and Properties of Bessemer Steel, *Trans. A.I.M.E.*, **116**, 137–158 (1935).

big-end-up ingots, tar with a low moisture content, a specific gravity of around 1.10, and viscosity above 300, free from dirt and foreign matter applied to the molds when they are at 200

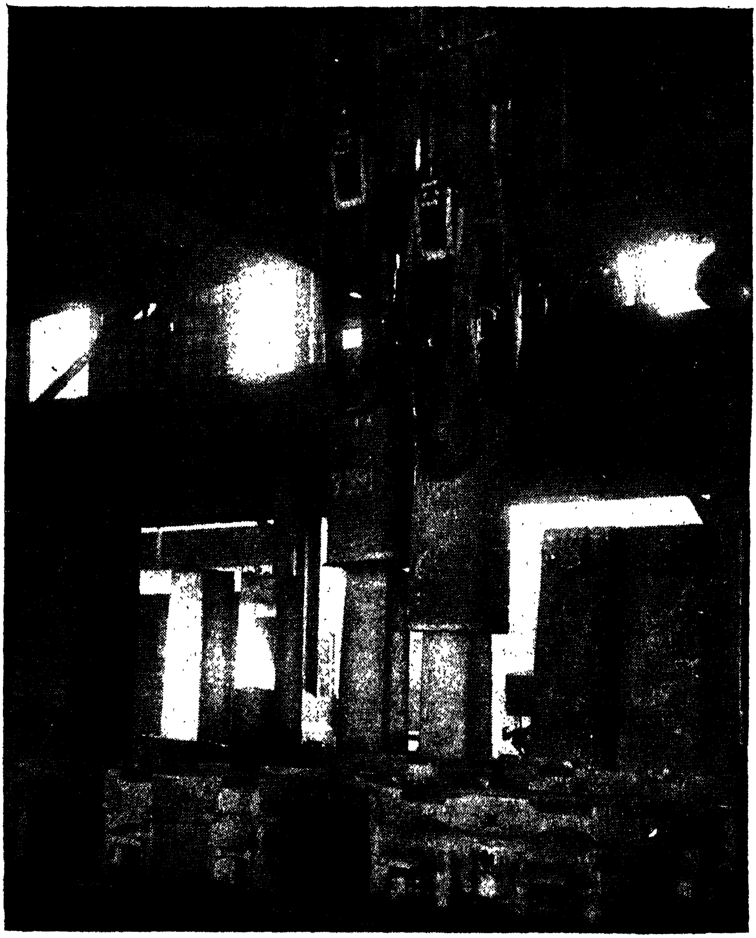


FIG. 10-II.—Stripping the mold from an ingot. (*Courtesy of the Youngstown Sheet and Tube Company.*)

to 400°F. has been found to be highly satisfactory. With big-end-up molds, tar cannot be used because the small bottom opening prevents proper draining of the excess tar. For this reason a mixture of graphite and water is used to spray the sur-

face, the water evaporating and leaving a thin graphite coating evenly distributed over the mold surface.

The metal may be teemed into the mold by supporting the ladle directly over each mold in turn and allowing the metal to fill the mold; or by pouring into a shallow refractory-lined vessel, called a "tun dish," having two or more suitably placed holes in the bottom through which the metal flows, thereby filling two or more molds at once. Another method is to teem the metal into a vertical brick-lined steel casting, called a "runner," which connects with an enclosed channel in the stool. The stool has a hole in the bottom connecting with this channel. By means of this arrangement, the mold is filled from the bottom. Since bottom pouring and pouring from the tun dish are used much more often in open-hearth and electric practice than in the Bessemer plant, discussion of these methods will be deferred until later.

After the heat is teemed, the metal is allowed to solidify in the molds and then the molds are removed. The machine that performs this operation is called a "stripper" and is usually of the traveling electric type. In stripping the big-end-down type of molds, the machine is so constructed that two jaws engage lugs on opposite sides of the mold and exert a strong upward pull on it while a ram holds the ingot firmly on its stool until the mold is loosened. In stripping the big-end-up type, the ingot must be pulled out of the mold—the reverse of the above procedure. If a hot top has been used, the refractory collar is removed and the jaws of this type of stripper grasp and pull upward on the top of the ingot while fingers hold the mold in place. Figure 10-II shows the stripper in action. Vibration of the mold is sometimes used to loosen big-end-up ingots. The most recent types can be loosened by punching the ingot out with the bottom plug. The ingots are then taken to the soaking pits in the rolling mill. Their further treatment will be covered in a separate section of the text.

Chemistry of the Process.—As has been previously stated, the purification of pig iron in the acid Bessemer converter consists in the oxidation of the impurities and some iron by the oxygen introduced in the air. The oxygen combines with the molten iron in the bath and forms iron oxide, FeO. This iron oxide acts as a carrier of the oxygen to the impurities and very little,

if any, gaseous oxygen gets through the metal bath. The reactions occurring in the process will be taken up in order.

The iron is first oxidized according to the reaction

$$2Fe + O_2 = 2FeO + 131{,}400 \text{ cal.}$$

The reaction is exothermic and, therefore, adds heat to the bath. The FeO formed is soluble in liquid iron and the violent agitation of the bath distributes it throughout the bath. A high local concentration at the point of formation does occur, however, and accounts for the rapid destruction of the upper surfaces of the tuyères.

Ferrous oxide, FeO, then reacts with silicon and manganese, oxidizing them according to the reactions

$$Si + 2FeO = SiO_2 + 2Fe + 64{,}600 \text{ cal.}$$
$$Mn + FeO = MnO + Fe + 25{,}200 \text{ cal.}$$

Both these reactions are exothermic and furnish most of the heat for the first part of the blow. Part of the metallic iron resulting from these reactions is caught by the slag but the majority of it goes back into the bath. The oxides of silicon, manganese, and iron react to begin the formation of a slag, since SiO_2 is acidic and MnO and FeO are basic.

$$SiO_2 + MnO = MnSiO_3 + 5{,}400 \text{ cal.}$$
$$SiO_2 + FeO = FeSiO_3 + 9{,}300 \text{ cal.}$$

The products of these two reactions are often written $MnO{\cdot}SiO_2$ and $FeO{\cdot}SiO_2$, being a slightly different way of writing the formulas of the same two compounds. More complex oxides are found at the same time by reactions analogous to these, but as they are of the same type they are omitted here.

While the silicon and manganese are being eliminated, very little reduction in the carbon content of the bath occurs. During the latter part of the blow, however, some carbon may be oxidized directly to CO and then to CO_2 by the following reactions:

$$2C + O_2 = 2CO + 58{,}320 \text{ cal.}$$
$$FeO + CO = Fe + CO_2 + 2{,}340 \text{ cal.}$$

When the elimination of silicon and manganese is almost complete, the second part of the blow begins with the rapid oxidation

of carbon, according to the reaction

$$FeO + C = Fe + CO - 36,540 \text{ cal.}$$

This reaction along with the one involving carbon and oxygen rapidly reduces the carbon. When the CO produced by these reactions reaches the nose of the converter, it is further oxidized by the oxygen in the atmosphere to CO_2 by the reaction

$$2CO + O_2 = 2CO_2$$

This latter reaction liberates considerable heat but takes place outside the converter and is the principal cause of the carbon flame during the final period of the blow. In normal operation, more than twice as much heat is lost by the further oxidation of CO to CO_2 (68,000 cal.) at the mouth of the vessel as is added to the bath by the primary oxidation of carbon to CO (29,000 cal.). Hence, when the converter is partly turned down and some of the CO burns to CO_2 inside the converter, the temperature of the bath rises.

With the drop in the flame, which occurs when the carbon content of the bath has fallen below about 0.05 per cent, the converter is turned down and the reactions cease. The carbon in the bath protects the iron from oxidation to a large extent but, after it is burned out, continued blowing will cause very rapid oxidation of iron. The blow must, therefore, be stopped as soon as the supply of carbon is burned out.

The reduction of the FeO to metallic iron is carried out by the manganese contained in the ferromanganese addition to the ladle while the recarburization is effected by the carbon contained in it. The manganese acts as a simple reducing agent in the reaction

$$FeO + Mn = Fe + MnO$$

The MnO formed is insoluble in the bath and rises as small particles into the slag covering. Sufficient time must be allowed for this transfer of oxygen from the iron to the manganese, and from the bath to the slag, or the resulting steel will be filled with small particles of MnO, called "sonims" or "inclusions," which are detrimental to the quality of the finished steel. Silicon acts in the same way as manganese.

THE BASIC BESSEMER PROCESS

This process is not in use in the United States, although considerable quantities of steel are made by this method in Europe. The method of removal of phosphorus by the use of a basic lining and additions of lime to the bath was first worked out successfully by Thomas and Gilchrist in 1878.

Pig iron for use in this process must contain a high content of phosphorus, generally over 2 per cent. This high value is necessary because the oxidation of phosphorus must maintain the temperature of the bath in the later portion of the blow. Furthermore, for the process to be a commercial success, the slag must be sold as a fertilizer on the basis of its phosphorus content. The silicon content of the pig must be as low as possible, since the SiO_2 formed by its oxidation is acid and attacks the expensive basic lining very rapidly. Since the manganese has to furnish the heat for the process during the early part of the blow, it must be well over 1 per cent in the pig iron charge.

Operation of the Process.—Since a larger volume of material must be blown in this than in the acid process to produce an equivalent amount of finished steel, the eccentric type of converter is usually used. The reason for this larger amount of material is that lime must be added to the molten pig iron to remove the phosphorus. Sulfur is removed in the process to some extent, but its removal is not controllable. The basic lining of the converter is made of calcined dolomite mixed with tar.

The molten pig iron and the necessary amount of lime are charged into the converter and the *foreblow* begins. Silicon and manganese are immediately oxidized to SiO_2 and MnO, respectively, adding heat to the bath. Lime reacts with some of the silica to form a calcium silicate while the rest of the silica attacks the dolomitic lining of the converter and combines with MnO to form a manganese silicate slag. As in the acid process, the oxidation of carbon starts as soon as the silicon and manganese are nearly all oxidized. The temperature of the bath is too high for the effective removal of phosphorus in the presence of carbon. What phosphorus is oxidized is immediately reduced again by carbon. The foreblow corresponds very closely to the blow of the acid process, with the exception of the lime reactions. It usually consumes from 10 to 12 min.

With the drop of the flame the *afterblow* starts. The object of this period is to remove the phosphorus by oxidation, although some sulfur is removed as calcium sulfide and calcium sulfate which are soluble in the basic slag. The phosphorus is oxidized to P_2O_5, which combines with lime and enters the slag.

$$4P + 5O_2 = 2P_2O_5 + 82{,}600 \text{ cal.}$$
$$P_2O_5 + 3CaO = Ca_3(PO_4)_2$$

The first reaction adds heat to the bath but the reaction goes on in spite of the high temperature because the carbon has been removed.

The flame gives no indication of when the phosphorus has all been removed and, since overblowing results in excessive oxidation of iron, the end of the blow should be carefully regulated. The operator knows from experience that a certain number of revolutions of the blower will remove one unit of phosphorus. Hence, a revolution counter on the blower shaft is started at the drop of the carbon flame and the afterblow is continued until the known amount of phosphorus is removed. This portion of the blow usually lasts about 5 min. The converter is then turned down, the blast shut off, and the metal poured into a ladle.

Recarburization and deoxidation are always carried out in the ladle in basic practice, and care is taken to remove the basic slag before this operation is attempted. The reason for this is that deoxidation in the presence of the phosphorus-containing slag results in reduction of the calcium phosphate and the reentrance of phosphorus into the metal. The FeO in the metal is reduced by the manganese in the recarburizer in the usual manner.

Status of the Process.—The basic Bessemer process was tried in this country at one time but the ores were found to be unsuitable for the manufacture of basic Bessemer pig. Furthermore, there was no market in this country for the slag at that time, and the educational campaign in the farming communities came too late to save the process.

The cost of the basic process is distinctly higher than that of the acid since the lining is more expensive and does not last nearly so long. The increased time of blowing and the addition of lime and removal of slag also add to the cost of the basic process. On the continent of Europe where very high phosphorus ores are plentiful and a good market exists for the slag, the

process has been successful. The Germans are able to make high-grade steel by the basic Bessemer process.

Suggested Questions for Study and Class Discussion

1. Give a typical Bessemer iron analysis. Why is the control of the pig iron analysis so necessary in the acid Bessemer process?

2. What are the chief uses of Bessemer steel?

3. Describe the main features of the Bessemer converter construction.

4. Discuss the chemistry of the acid Bessemer process.

5. What methods are employed to control the FeO content of the metal?

6. Why is it important to control the FeO content?

7. What methods are employed to regulate the temperature throughout the blow?

8. How long does it take to blow a heat of Bessemer steel? What factors cause this blowing time to vary? Why?

9. Define deoxidation. What connection exists between deoxidation and steel quality? How is deoxidation controlled? What is a recarburizer?

10. How does the blower know when the steel is ready to pour?

11. What are the reasons for using mold coatings? Why use tar rather than salt or graphite as a mold coating?

12. In what way does the basic Bessemer process differ from the acid? Why is the basic process not used in this country to any extent?

CHAPTER III

THE BASIC OPEN-HEARTH PROCESS

Most of the steel in this country at the present time is made by the basic open-hearth process. Since 1908, when this process first passed the Bessemer in point of annual production, the open-hearth has increased its advantage and seems likely to remain the predominant steelmaking process in this country for some time to come. As compared with the Bessemer process, the ores that can be used for making basic open-hearth pig are much more numerous and cheaper, the control of the process is much better since the time taken for purification is longer, and the product is, therefore, much more uniform and of superior quality.

The success of the open-hearth process rests upon the invention of the regenerative principle of heating by William Siemens in 1858. It will be remembered that in the manufacture of wrought iron, the highest temperature attainable in the reverberatory furnace is insufficient to melt the iron completely, and the purified iron remains in a pasty semisolid state. The regenerative principle invented by Siemens consisted briefly in using the hot waste gases from the combustion chamber to heat the air used for combustion to a high temperature before its introduction into the furnace. The heat generated by the combustion of the fuel was in this way relieved of the burden of heating the large amount of air needed for burning the fuel and this extra heat was then made available for raising the temperature of the charge. The result was that the regenerative furnace would completely melt the charge and the purified metal could be tapped from the furnace in a highly fluid state. This regenerative principle will be studied in detail a little later.

The Open-hearth Plant.—The actual placement of the various pieces of auxiliary equipment with respect to the furnaces themselves varies so widely from plant to plant that only a general idea of plant layout can be given here. The following description is believed to include average practice, at least in the newer plants.

The furnaces themselves are set end to end along the center of a long steel building designed to house them. The charging floor extends along the front, or charging side, of the furnaces at the level of the hearth, and a track runs along the floor close to the furnaces on which the solid materials are conveyed to the furnace for charging. In the space above this floor and the furnaces, two or more traveling electric cranes operate and bring the molten materials to the furnace for charging. Underneath the charging floor are located the regenerators and the flues that conduct the gas and air to and from the furnaces. The stack is usually placed just outside the building on the charging side opposite the middle of the furnace.

FIG. 1-III.—Charging floor of an open-hearth furnace showing a charging machine in operation. (*Courtesy of Jones & Laughlin Steel Corporation.*)

On the tapping side of the furnaces, the pouring floor is approximately 15 ft. lower than the charging floor. It is constructed in this manner in order to make the tapping and slag disposal more convenient. The tapping floor, or pit, is also spanned by electric overhead cranes which handle ladles during tapping and teeming. The teeming platforms extend along the far side of the tapping floor and are elevated approximately 10 ft. above the tapping floor.

The hot-metal mixer or mixers are usually located at one end of the charging floor. The mixer is a refractory-lined closed vessel in which molten iron from the blast furnace is stored until needed by an open-hearth furnace.

If producer gas is used as fuel, the gas producers are located on the charging side of the furnaces and just outside the open-hearth

building. They are placed as close to the furnaces as possible in order to minimize heat loss and deposition of tar in the mains while the gas is traveling from the producers to the regenerators. Two gas producers are usually needed for each furnace. The gas producer is a cylindrical brick-lined steel shell, mechanically rotated. Air and steam are passed through a bed of hot carbon

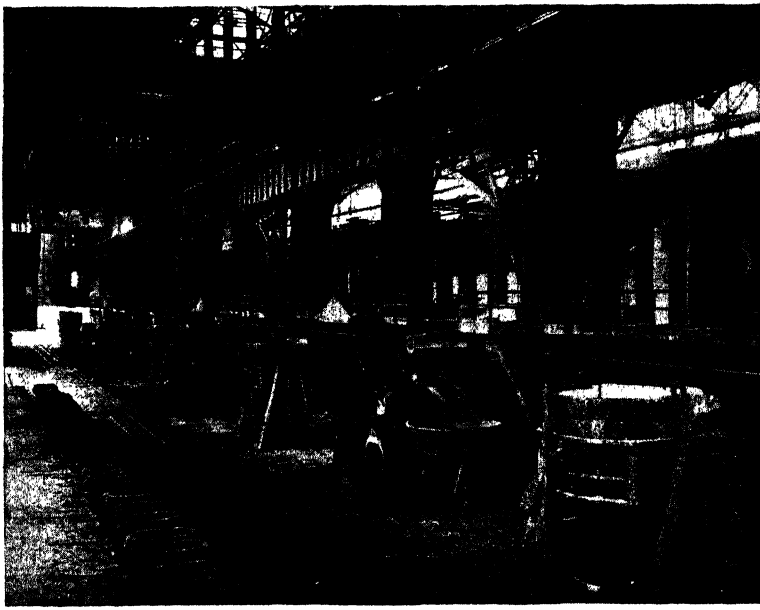


FIG. 2-III.—View of the tapping side of the open-hearth furnace from the pit.

(a high volatile and low sulfur bituminous coal). The reactions that occur are

$$C + O_2 = CO_2$$
$$CO_2 + C = 2CO$$
$$H_2O + C = H_2 + CO$$

The resulting gas contains 5 to 9 per cent CO_2, 18 to 27 per cent CO, 10 to 18 per cent H_2, 48 to 55 per cent N_2, and 2 to 4 per cent hydrocarbons contained in the coal or distilled from it, principally CH_4 (methane). Of these CO, H_2, and the hydrocarbons are the only combustibles, the CO_2 present being due to the incompleteness of the second reaction, and the nitrogen being

present in the entering air. With the increase in fuel-oil production most plants are using oil as fuel because it gives a sharper, hotter flame and is much easier to handle in the shop.

Next to the furnaces themselves, probably the most essential piece of equipment in the open-hearth plant is the charging machine. This machine is capable of charging all the solid materials necessary for a furnace in about an hour, while hand charging would take much longer and the extra time consumed

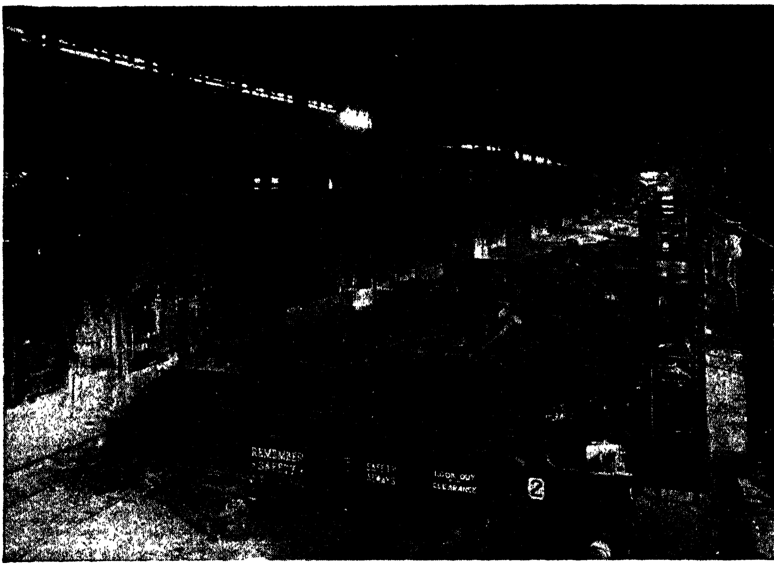


FIG. 3-III.—Open-hearth charging machine. (*Courtesy of the Wellman Engineering Co.*)

would be a serious drawback to the process. Charging machines are of two general types: the high and the low. The low type, which is the more common, will be described here.

This electrically operated machine consists of two main parts. The bottom truck is a strong steel frame mounted on flanged wheels which run on a track about 20 ft. wide laid in front of the furnaces. The charging carriage moves back and forth on a track laid on the frame at right angles to the motion of the truck itself. On the carriage is mounted a long bar, called the "peel," or charging bar, which is hollow to accommodate the lock rod. The peel is capable of being revolved.

The solid materials are brought to the furnace in cast-steel charging boxes of 20 to 25 cu. ft. capacity, placed on buggies that run on the track between the charging machine and the furnaces. The charging boxes, usually about 5 ft. in length, are provided with a socket on one end into which the end of the peel can be inserted and locked into place with the lock rod. In operation, the charging machine engages with a charging box on a buggy and, by moving the charging machine, the whole train of buggies can be moved until the box in question is directly in front of any particular furnace door. The machine then picks up the box, thrusts it into the furnace, and turns it upside down, thus dumping its load. It then turns it right side up, pulls it out of the furnace, replaces it on the buggy, and engages with the next box on the buggy. The machine is capable of emptying more than one box per minute.

The rest of the equipment, such as ladles, molds, and the stripper, is like that described for the Bessemer plant but is much larger in design.

THE STATIONARY OPEN-HEARTH FURNACE

The basic open-hearth furnace is of long, narrow, rectangular construction with an arched roof. The furnaces of recent construction have at least 200 tons capacity, and the hearth is, therefore, about 45 ft. in length, 15 ft. in width, and 30 in. in depth. Figure 4-III is a cross section of the middle of the furnace as seen from the end of the furnace and Fig. 5-III is a longitudinal cross section of the hearth.

The hearth of the furnace, as well as the walls, rests upon a heavy concrete foundation. The hearth is started by laying thick plate on heavy I beams supported by strong reinforced concrete piers, which form an air space for cooling purposes. On this plate are laid 4½ in. of first-quality firebrick, then 13½ in. of chrome brick. The hearth lining consists of a mixture of ground calcined magnesite and basic open-hearth slag sintered in place in successive layers. A newer method of hearth lining consisting of a commercial magnesite mixture rammed in cold has come into prominence in recent years. The finished hearth has the shape of a shallow dish, curving upward at the sides and at both ends of the furnace. The back wall of the furnace (tapping side) is made less steep than the charging floor side in

order that it may be repaired more easily. The magnesite brick lining is carried up the side walls of the furnace to a point just above the hearth lining. A course of neutral chrome brick is

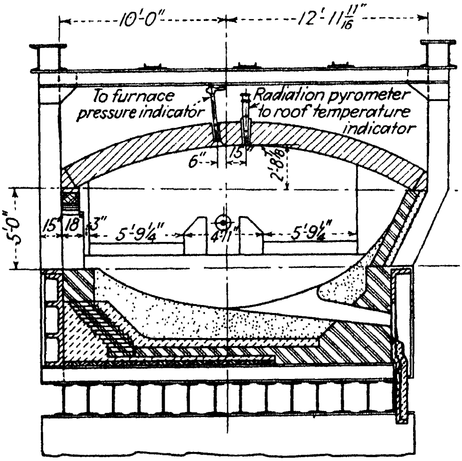


FIG. 4-III.—Cross-sectional elevation through the middle of the furnace.

placed at the slag line where the greatest erosion occurs and the rest of the furnace interior is constructed of silica brick. In some plants the entire front wall is constructed of a chrome magnesite

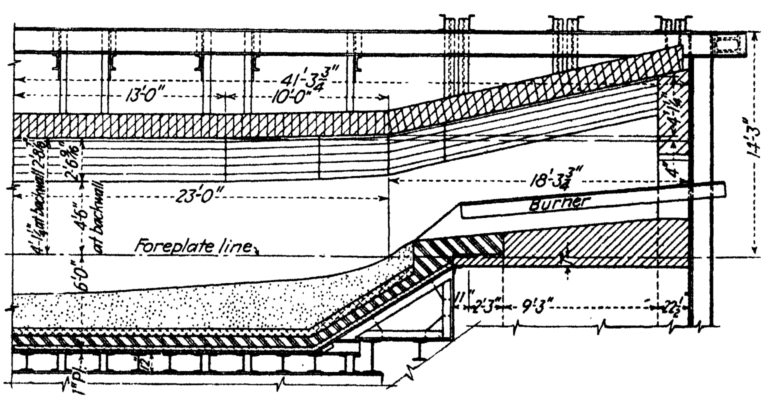


FIG. 5-III.—Longitudinal sectional elevation through the center of the hearth.

brick if the operator feels the expense is justifiable. The bottom material is carried up the sloping back wall to a point near the roof.

The walls of the furnace are strongly reinforced with steel slabs and channels. The front or charging side is pierced with five arched doors from 3½ to 5 ft. in width, equally spaced along the hearth of the furnace, the sills of which are placed just above the slag line. The brickwork at each door is protected by a water-cooled frame upon which the door slides when raised or lowered. The doors are constructed of steel, lined with silica brick, are

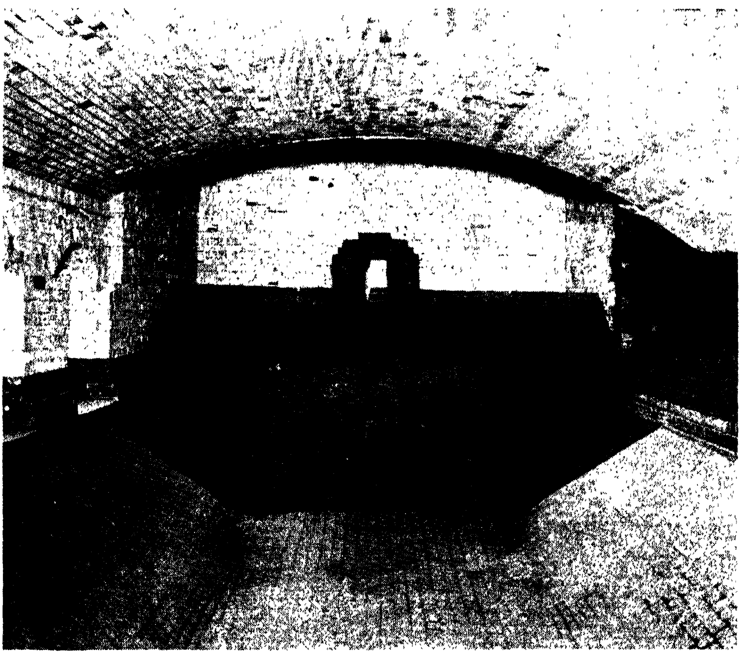


FIG. 6-III.—View of one-half of newly relined basic open hearth. (*Courtesy of Bethlehem Steel Company.*)

water-cooled, and are raised by either hydraulic or water power. Each door has a hole 4 to 6 in. in diameter in its center to permit observation of the bath without raising the door. Most plants are doing away with hydraulic power around the furnace where-ever possible, as many leaks occur, which are very detrimental to hot silica brickwork. The roof, also of silica brick, is arched and is from 15 to 18 in. thick. Some roofs are built 3 in. thicker along the back, that part of the roof being subjected to the greatest wear. Many plants have found a savings in fuel cost by insu-

lating the furnace walls, but furnace roofs are seldom insulated as natural air cooling prolongs the life of this brick.

The bottom of the back wall of the hearth is pierced at its exact center for the tapping hole which is about 8 in. in diameter and 5 ft. in length and is provided with a cast-iron lip on the outside of the furnace into which a brick-lined steel spout fits when the metal is being tapped from the furnace. The hearth bottom is sloped toward the tapping hole from all directions in order that the entire furnace may be drained. The slag or flush hole is placed about 15 ft. from the taphole and from 4 to 6 in. above the top of the metal (bath) surface. The flush spout can be attached to a lip provided at the outside of the furnace. On most furnaces of recent design the slag is run off over the middle door and down into a cinder pot on the regenerator floor.

The design of the ports through which the air and fuel enter the furnace varies considerably with the type of fuel used to heat the furnace. The various fuels used are natural, coke-oven, and blast-furnace gas (or a mixture of any of the three), producer gas, powdered coal, fuel oil, and tar. Producer gas, or mixtures of producer and coke-oven or blast-furnace gas, is the only fuel that may be preheated without decomposition. Other fuels are introduced into the furnace through special burners; a different burner design is required for the efficient utilization of each type of fuel. Powdered coal is injected into the furnace by means of compressed air, and the oil or tar fuels by steam. Regardless of the fuel used, the air for combustion is always preheated as the efficiency of the process depends upon this regenerative principle.

In the case of preheated gaseous fuels, these require two ports in each end of the furnace. The air port is built over and around the small gas port. The ports are always inclined toward the hearth and the brickwork between them is water-cooled. The spaces back of the brickwork below the ports (bulkheads) are taken up by large hollow castings, air-cooled to prevent burning out of the brickwork. The refractories in this portion of the furnace suffer a lot of punishment from the intense heat and must be carefully designed and constructed of the best materials obtainable or rapid failure of the ports and bulkheads will occur.

The flame is directed downward by the design of the ports in such a manner that the gases sweep across the bath as they travel to the outgoing end of the furnace.

A great many plants today use fuel oil because of its flexibility and thermal value. For this fuel, a single port pierced by a water-cooled burner is used. The oil is atomized with steam just before it enters the furnace. The steam is usually super-

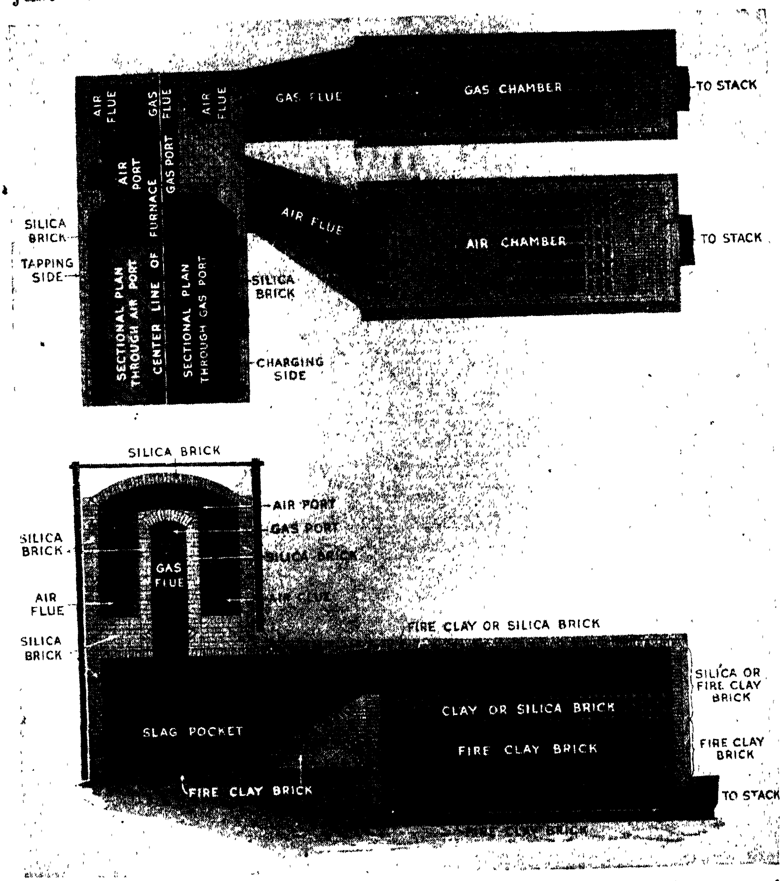


FIG. 7-III.—Section of furnace showing regenerators and uptakes. (*Courtesy of Harbison-Walker Refractories Co.*)

heated by running the steam line through the regenerator chamber, and it reaches a temperature as high as 800°F. The oil is piped to the furnace from storage tanks at a pressure of 125 to 175 p.s.i. and a temperature of 150 to 200°F.

The regenerative principle of heating the air and most of the gaseous fuels prior to their introduction into the furnace is

utilized by constructing four chambers of firebrick below and in front of the furnace. One regenerator for gas and one for air are placed side by side on each end of the furnace. Figure 7-III shows their size with respect to the furnace. Each regenerator is built of firebrick upon a concrete foundation and is nearly filled, except for space at the top and bottom, with brick checkerwork. The gas chambers for a 200-ton furnace are about 30 ft. long, 10 ft. wide, and nearly 17 ft. high. The air chambers are the same length and height but are about 12 ft. wide. The air chamber should be larger than the gas chamber because proper combustion requires a larger volume of air than gas. Each pair of regenerators (one for gas and one for air) is built close together, and brick flues called "fantails" (because of the shape of the roof of this flue) lead from each regenerator to the bottom of the uptakes. The uptakes are also of brick and lead the gas and air to the ports at each end of the furnace. When oil is used as a fuel, the gas chamber is also used to preheat air. Sometimes the gas and air chambers are combined under one roof.

When the furnace is in operation, gas and air are admitted to their respective regenerators at one side of the furnace, are heated, and flow through the flues and uptakes in succession. They unite and burn upon being projected from the ports, and the intensely heated products of combustion sweep across the furnace and are drawn through the ports, thence down and through the regenerators on the other side of the furnace. In passing through these regenerators the hot waste gases heat the brickwork to a bright red heat and pass off through the exhaust flues to the stack. The stack furnishes the draft necessary to draw the gases through the ports and regenerators upon leaving the furnace. The flues leading to the regenerators are equipped with mechanically operated valves and are connected in such a manner that the direction of flow of the gas and air can be reversed every 15 or 20 min. Shops are now equipping with automatic reversal mechanism which reverses the furnace when the regenerator temperature difference on the two ends reaches an established degree. Upon reversing the direction of flow, the set of regenerators that had been receiving heat from the waste gases now becomes the one that preheats the gas and air, and the set that had previously been heating the gas and air becomes the one that is storing heat from the waste gases in preparation for the next

FIG. 8-III.—Model of an open-hearth-furnace unit.

reversal. In this way, the gas and air enter the furnace through the ports at either end of the furnace alternately, the air being preheated to about 2000°F. and the gas to a somewhat lower temperature.

The reversing valves used at the present time are mechanically operated and water-cooled. The flues on each side of the furnace have an opening for admitting air and a damper to shut off the flue. The air inlet is closed by a saucer-shaped casting suspended by cables and connected to the reversing mechanism. The suspension is adjustable to allow a control on the volume of air. The damper that closes the flue and is placed between the air

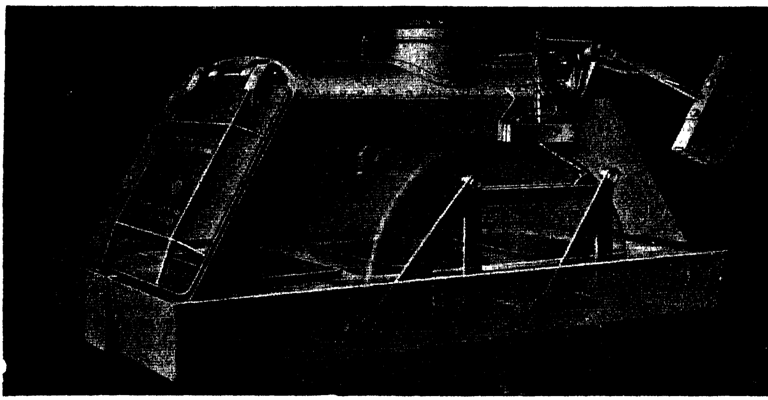


FIG. 9-III.—Phantom view showing general design and construction of W-S-M gas reversing valve. (*Courtesy of the Wellman Engineering Co.*)

inlet opening and the stack is usually of a design inclined at 80 deg. to the horizontal and slides on a water-cooled frame. The height of this damper is also adjustable and is connected by cable to the reversing mechanism. The reversal is synchronized so that when the air saucer is up and the damper down on one flue, the air saucer will be down and the damper up on the opposite flue. When the direction of the flow of gases is reversed, both damper and air saucers move simultaneously. When preheated gaseous fuels are used, an encased three-way valve arrangement must be used to introduce the fuel into the flues.

Operation of the Furnace.—For the operation of a 200-ton stationary furnace three men are required: a first helper, a second helper, and a third helper. Besides these a melter foreman is in charge of several furnaces and superintends their

operation. Under ordinary operating conditions, the first helper is in charge of the furnace except during the tapping of the heat. If anything unusual occurs during the working of the heat, the melter takes charge. Otherwise, the first helper superintends the charging and working of the heat, taps the heat under the direction of the melter, and directs the repair of the hearth for the next heat. The second helper assists the first helper in the above operations in addition to preparing the furnace additions, and recarburizers. The third helper assists in making bottom at his own furnace and on all others under his melter foreman and assists the second helper in cleaning, preparing, and placing the steel runner on his furnace.

Great care is required in starting up a new furnace in order to prevent too rapid heating of the brickwork and consequent cracking and explosions, especially when the furnace is fired with producer gas. The interior of the furnace is first carefully dried out with wood or gas fires for 12 hr. and the temperature gradually increased for another 8 hr. Heating is then started with the fuel regularly used in the furnace, and the temperature is increased gradually until the proper hearth temperature is reached for melting slag (about 2800 to 2900°F.). The bottom is then covered with a thin layer of ground magnesite and a little ground basic slag is scattered on top. Several hours are necessary to fuse these materials, fill the spaces between the bricks, and make the bottom solid.

The building of the bottom can now be started. The usual bottom is made of a mixture of about 75 per cent magnesite and 25 per cent basic slag, ground to pass a ¼-in. mesh. A ¼-in. layer of this mixture is scattered over the sides and bottom of the hearth and sintered into place by the heat of the flame for at least 3 hr. Successive layers are put in and the sintering process repeated for each until the bottom and banks are built up to a thickness of about 11 in. This procedure may take 10 days to complete. The tapping hole is then cut through from the outside, filled with burned dolomite, and capped with a clay plug on the outside. Several tons of basic slag are then shoveled on the banks, melted, and allowed to seep into banks and bottom until the hearth is solid. The excess slag is then tapped out, the banks and bottom are dressed up with dolomite, and then the fuel is taken off and the hearth allowed to chill for an hour; the furnace

is now ready for charging. There are several new types of bottom material in use in many plants. These consists mainly of a mixture of magnesite and basic slag with a high iron content bonded with water and rammed into place cold. When the furnace is lighted, dried out, and brought up to temperature, the hearth is saturated with basic slag and chilled as above and is then ready to charge. This method produces a good solid bottom and saves much time and fuel.

Maintenance of the Furnace.—During the operation of a furnace, there is a considerable amount of wear on the furnace bottom, particularly at the slag line. This portion of the furnace should be patched after every heat; raw dolomite is used for patching unless a deep hole has developed in the lining, in which instance a synthetic dolomite is used, since it sinters into place more readily than the raw dolomite or magnesite. Since a considerable amount of raw dolomite is necessary to patch the lining properly (10,000 to 11,000 lb. per heat for a 200-ton furnace), the patching is frequently done with a mechanical device that throws the dolomite to the corroded parts of the lining. If the lining is not patched after each heat with materials of the proper composition, serious leaks in the lining may occur which cause the loss of the metal on the hearth and may necessitate a complete rebuilding of the furnace. When holes occur in the bottom of the hearth, the metal in them is either rabbled out (splashed out with a long steel hoe) or blown out with compressed air. If the hole is shallow, it is filled with a synthetic dolomite and the fuel put on the furnace until slag from other parts of the hearth has run over the patch. If the hole is deep, it must have several layers of magnesite sintered into it, or the same hole may occur on the next heat. The taphole is also subject to constant erosion and when it has become enlarged to more than 10 to 12 in., a pipe about 6 in. in diameter and 5 ft. long is laid in the hole, and chrome ore is packed around it to fill the larger opening.

The furnace gases acquire quite a velocity in their passage through the furnace and consequently carry off a large amount of dust and slag particles. This is particularly true when ore or sinter is charged, or if the furnace is fired with powdered coal, as the fine ash particles are swept out of the furnace with the waste gases. At the bottom of each downtake there is a slag pocket with an area of about 170 sq. ft., and a bridge wall about

10 ft. high which separates this pocket from the regenerators. The bridge wall causes a change of direction in the flow of waste gases and causes them to drop most of their slag and dust particles. In spite of these precautions, however, some dust and slag particles get into the regenerators and flues and slowly clog the openings between the bricks of the checkerwork. When the regenerators are so badly clogged that they restrict the flow of gases and will no longer preheat the entering gases efficiently, the furnace is shut down and repairs made.

The life of a furnace roof is usually somewhere in the neighborhood of 300 heats although it varies widely with furnace operation. When the roof falls in or a fall-in seems to be imminent, the furnace is shut down and repairs made. Even though the ports for preheated gaseous fuels are water-cooled, they slowly melt away owing to the intense heat of the waste gases received by them on every other cycle. When the ports wear away too much, the angle at which the gases enter the furnace is changed and some portion of the furnace is then usually overheated and burning out occurs.

The reversing valves and dampers need constant inspection as they are subject to heat from the exhaust gases and warp, become choked with dust, fail to fit tightly, and therefore leak.

The Tilting Open-hearth Furnace.—There are two main types of tilting furnaces, so called because the furnace itself is mounted on a roller mechanism that tips it forward or back. In the Campbell type, the hearth of the furnace is constructed so that the center or axis of tilting is coincident with the center of the ports. A little clearance is provided between the uptakes and the furnace proper, and a fairly tight joint is made by the use of water-cooled castings. In this way, the furnace may be tilted without shutting off the gas and air.

In the other type of tilting furnace, the Wellman, the ports move with the hearth when the latter is tilted. The ports are seated in a water tank which makes an airtight connection with the regenerators when the furnace is in a horizontal position, but breaks the connection when the furnace is tilted. Aside from these differences, both types of furnace are constructed like the older and more common stationary type, with the exception that the tilting furnace has no taphole but has a pouring spout, as shown in Fig. 10-III.

In comparing these two types of furnace, the first cost and upkeep of the Wellman are usually less than those of the Campbell. The Campbell type, however, has the advantages that go with being able to maintain the flame when the furnace is tilted. The bottom can be repaired and the dolomite sintered with the furnace in any position; cold air will not enter the furnace when it is tilted as happens in the Wellman type; finally, a larger amount

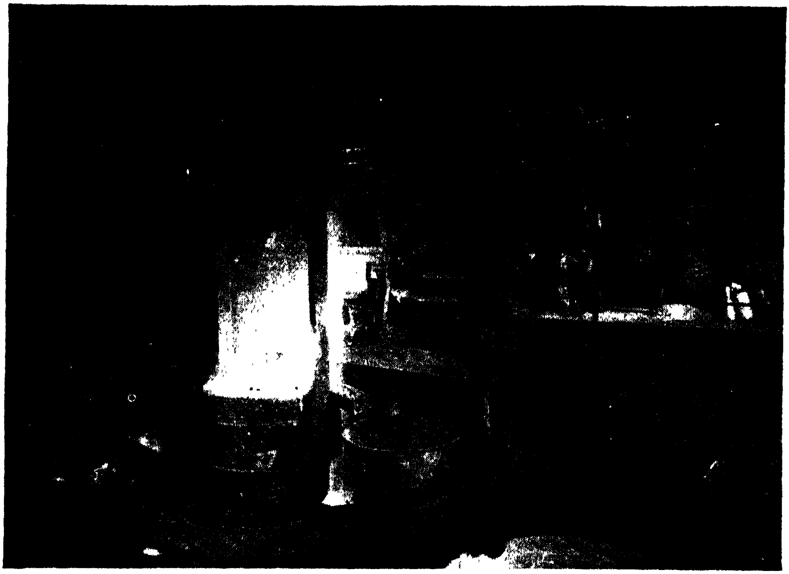


Fig. 10-III.—A 200-ton tilting open-hearth furnace. (*Courtesy of Bethlehem Steel Company.*)

of ore can be used and the boiling slag retained in the furnace by tilting it so that the slag will not boil over through the doors.

In comparing the tilting with the stationary types of furnace, the tilting furnaces are more expensive to install and require maintenance of and power for the machinery that operates them. The special arrangements of ports and uptakes together with the water-cooled joints cause added expense and trouble.

On the other hand, the taphole of the stationary furnace is the cause of some difficulty as it is often either hard to open or hard to keep closed tightly. The tilting furnace removes this difficulty, the slag can be poured off at any time, and the charge can

be tapped on very short notice. The tilting furnace is probably of more advantage in the foundry than the steel mill, since furnaces are smaller, usually hand-charged, and tapping is more frequent.

The Basic Open-hearth Charge.—One of the most important reasons why the basic open-hearth process is the principal steelmåking method in this country at the present time is that the furnace charge can be varied so widely to suit economic conditions and still produce a uniformly good quality of steel.

The original open-hearth process as developed by Siemens made use of an acid lining and the charge consisted of pig iron and ore. In order to remove phosphorus, a basic bottom was later substituted and limestone was charged to remove the phosphorus from the metal. The oxidation of the impurities was performed by the furnace gases and by the ore which was fed into the molten iron at frequent intervals. This is called the "pig and ore process" and is seldom used in this country, owing principally to the large amount of steel scrap that is generally available. The steelmakers, therefore, turned to the pig and scrap process in which steel scrap is charged into the furnace, is more or less completely melted, and then molten pig is poured in. If cold pig is used, it is charged on top of the scrap. The oxidation is carried out by means of the oxidizing furnace atmosphere and by small additions of iron ore to hasten the process.

The practice followed in a given plant depends to a large measure upon the cost of pig iron versus scrap. In those plants which have blast-furnace facilities and with the existing price of pig iron, which is cheaper than some grades of scrap, the total charge will average 60 per cent molten iron. The use of molten iron has an additional advantage in that it can be charged much more rapidly than scrap.

The pig iron produced for the basic open-hearth process has the following approximate composition:

	Per cent		Per cent
C	4.00	S	0.04
Mn	1.50	Si	1.00
P	0.25	Fe	93.00

The best silicon range in the iron is from 0.80 to 1.20 per cent with an average of about 1.00 per cent. If the silicon in the iron is high, the slag will be acid and excessive amounts of burnt lime must be used to correct slag basicity. Low silicon iron produces a slag that tends to make the heat slow working.

The basic open hearth can eliminate as much as 1.00 per cent phosphorus from the charge. This has made it the greatest tonnage producer of steel today.

Since sulfur is probably the most difficult element to remove, the percentage of it in the iron should be kept at a maximum of 0.040 per cent. The oxidizing slag of the basic open hearth tends to retard the reaction of sulfur elimination, and scrap and slag usually absorb sulfur as SO_2 from the furnace gases; hence, the sulfur content of the fuel should be kept at a minimum, especially in the use of producer gas and by-product coke-oven gas.

The manganese in the pig iron serves several useful purposes and may, therefore, be quite high. When the manganese content is high (1.25 to 1.75 per cent), the pig loses much of its sulfur between the blast furnace and the open hearth (principally in the mixer) due to the formation of MnS. Also, the fluidity of the open-hearth slag is increased with increasing manganese. This makes for a faster working heat. One of the main reasons for having the manganese content high in the pig iron is its effect on the residual manganese. A high residual manganese causes a pronounced saving in the ferromanganese additions in the ladle. A residual manganese of 0.20 to 0.25 improves the quality of low carbon killed steels.

Chemical Reactions in the Bath.—The elimination of the elements silicon, manganese, phosphorus, carbon, and sulfur starts immediately after the addition of the molten pig iron. The elimination of the elements, with the possible exception of sulfur, is brought about by a process of oxidation. The oxygen is supplied from the ore, from the iron oxide formed by the oxidation of the scrap, and from the gases that pass over the bath. The following reactions show how the form and characteristics of the various elements are changed so they may be partly removed from the bath.

Silicon:

$$Si + 2FeO = SiO_2 + 2Fe$$

This reaction is quite rapid and goes practically to completion as is evidenced by the fact that the average heat will contain less than 0.10 per cent silicon at tap.

Manganese:

$$Mn + FeO = MnO + Fe$$

In comparison to silicon the reaction is less rapid. The manganese residual or amount retained in the bath is considerably larger; and this amount is more sensitive to the oxidation of the bath, slag conditions, and temperature.

Phosphorus:

$$2P + 5FeO = P_2O_5 + 5Fe$$

This reaction probably occurs next in the order of oxidation of the elements. It differs from the previous ones in that it reverts rapidly from the slag to the metal if the slag conditions are not suitable for retaining it. The amount of phosphorus remaining in the metal bath is largely dependent upon the lime-silica ratio of the slag.

Carbon:

$$C + FeO = CO + Fe$$

This reaction does not occur to any extent until the silicon and manganese have been fairly well eliminated. This element can be eliminated from the bath with fair speed by the use of ore down to about 0.05 per cent and even lower by the use of excess ore and other special means.

Sulfur:

$$FeS + CaO = CaS + FeO$$
$$FeS + CaO + C = CaS + CO + Fe$$

The removal of sulfur, which is present in the bath as FeS, is very uncertain; however, the foregoing reactions show the means by which it is eliminated from the bath. High manganese in the charge aids its removal, resulting in the formation of MnS, a compound much preferred to FeS. Desulfurization is favored by very basic slags with fluidity maintained and high temperatures. Highly oxidizing slags retard the reactions. The best means to control sulfur is to have low sulfur content in the charge.

Charging Procedure.—There are three types of heats charged in open-hearth furnaces depending on shop conditions and locality.

The type most prevalent is the hot metal and ore heat where an abundance of hot iron permits the use of an excessive iron charge. In these heats great care is essential to obtain a large flush of the initial slag so that the lime charge can be kept at a minimum. Very little scrap is charged on the bottom, and the amount of limestone charged on it is about 6 per cent of the metallic charge. The lime is well covered with the ore or sinter charged so that no lime rises from the bottom until the heat has been flushed, or it would make the slag too thick to obtain a good flush. After the ore has been charged on the limestone, the furnace is charged with the required amount of scrap and each door is banked with a dam of raw dolomite about 2 ft. high to hold the increased volume of initial slag in this type of heat. These charges contain from 55 to 80 per cent molten iron.

The second type of charge is the hot metal and scrap charge which is used when there is some molten iron available but insufficient to use over 45 per cent molten iron in the charge. This type differs from the foregoing charge in that no ore is charged and therefore with no slag flush an 8 per cent limestone charge must be carried to counteract the oxidized silicon from the hot metal. The bottom is covered well with scrap and the limestone is charged evenly upon it. Burnt lime, sometimes charged if the furnace is working "sharp," greatly lessens the period of lime boil but it has the disadvantage of a tendency to stick to the bottom. The scrap is charged after all the lime has been added. If light scrap is charged, it is often necessary to melt down some of the scrap before adding the total scrap charge.

The third type of charge is a cold metal charge and is used when there is no molten iron available. This is the slowest of the three types as it requires more heat to liquefy the cold iron before it will react with the molten scrap. The bottom is usually scrapped heavily and burnt lime is charged instead of limestone to speed up production. Some plants charge the cold iron as soon as the scrap has melted enough to allow room for the iron charge, while others prefer to melt the scrap almost to "soup" before adding the pig iron. This type is similar to the hot metal scrap charge except for the fact that a slightly greater percentage

of iron must be charged because it is in the cold form. Because of the greater amount of iron charged, more lime must be charged to counteract the greater amount of silicon resulting from the iron.

Melting Down.—For the rapid melting of scrap the furnace should be charged as soon as possible after the previous heat has tapped so that the regenerators will be kept as hot as possible. As soon as the heat has been tapped, the draft should be cut down and kept that way until the cold materials have been charged. This keeps the checkers from cooling off excessively while the fuel is off to make bottom and the furnace doors are open in charging. This is very easily done by closing the stack damper. On furnaces fired with oil or tar, a short hot flame is advantageous in cutting the scrap. The flame characteristics of other fuels are not so easily controlled.

The open-hearth flame is the chief source of oxygen in the process as the excess air used to obtain the high temperature in the furnace makes the flame and furnace atmosphere strongly oxidizing. During the melting of the scrap, the FeO produced by scrap oxidation plays an important part in the working of the heat since the concentration of the FeO in the slag when the heat is melted has a great effect on its oxidizing power during the finishing of the heat. This is necessarily true since a major part of the oxidation takes place through the oxidation of FeO in the slag to Fe_2O_3 by the furnace gases and its subsequent reduction to FeO by reaction with the metalloids in the bath.

The amount of FeO produced by oxidation of the scrap can be controlled through several factors. The amount of excess air used in burning the fuel is important since the greater the amount of free oxygen over that theoretically required for combustion, the greater will be the oxidizing power of the gases and hence the greater the amount of oxidation of the scrap. The size of the scrap has a definite effect on the amount of oxide produced, *i.e.*, the larger the individual pieces, the smaller the surface for oxidation. Thus, a charge of crop ends will produce about one-tenth as much FeO while melting down as does light scrap. The age of the furnace is also a factor in that, as it gets older and the regenerators become clogged, the time needed to melt a given amount of scrap will be longer and more FeO will be formed than in a sharp working furnace.

While the scrap is being melted down, it undergoes oxidation from the water vapor, carbon dioxide, and free oxygen in the furnace gases according to the reactions

$$Fe + H_2O = FeO + H_2$$
$$Fe + CO_2 = FeO + CO$$
$$2Fe + O_2 = 2FeO$$

A very small amount of the FeO is further oxidized to Fe_3O_4.

As soon as the surface of the limestone is heated above 1652°F., it begins to decompose into CaO and CO_2, according to the equation

$$CaCO_3 + \text{heat} = CaO + CO_2$$

Hot-metal Additions.—On ore heats, the hot-metal additions should never be made until the scrap has been heated to the temperature of the hot metal. If the hot metal is added while the scrap near the bottom of the furnace is cold, some of the metal freezes on the cold scrap and a poor flush and a delayed heat result. On the other hand, if the operator waits too long before adding the hot metal, a violent reaction occurs and most often a mess of slag on the floor is the result. Small amounts of cold iron may be used on hot metal, scrap, and ore heats with no loss in heat time. The introduction of a small amount of cold iron, if it has been necessary to wait for the hot metal, will help prevent the violent reaction when the hot metal is added.

On hot-metal scrap heats the iron may be added over a longer period of time than on the ore heats with no loss on heat time.

Hot metal is brought to the furnace from the mixer in a ladle by an overhead crane. After the charging machine has placed a brick-lined spout in the door opening, the ladle is tipped and the iron poured in. Best results are obtained by pouring the metal in the furnace slowly, allowing it to mix with the semi-molten scrap.

Slag Formation.—Basic open-hearth slag results essentially from the silicon in the iron oxidizing to silica, SiO_2, and from the manganese oxidizing to MnO. Some carbon is also oxidized during this early slag-forming period. The MnO and SiO_2 react to form manganese silicates

$$x\text{MnO} + SiO_2 = x\text{MnO}\cdot SiO_2$$

Ferrous silicates are also formed by the reactions of which the one below is a type,

$$FeO + SiO_2 = FeO \cdot SiO_2$$

The silica combines with the lime coming up from the bottom during the lime boil to form dicalcium silicate, $2CaO \cdot SiO_2$. When enough lime has gone into solution to neutralize the silica, the excess lime available acts upon the phosphorus, sulfur, and the iron oxides present. These reactions will be discussed later.

The Flush and Ore Boil.—The success in making good heat time and quality steel on ore heats depends on getting a good flush of the initial slag. To obtain a good flush several factors should be taken into consideration when charging. A dense, dry, high iron content ore or well-sintered fine ores should be charged; the lime must be well covered with ore so that none will rise and enter the slag until the heat is through flushing; and sufficient ore should be charged to react over a long enough period of time to give a good flush.

The flush hole should be at the proper level and wide enough to allow a rapid flush, and closed with coal and raw dolomite so it will not permit the initial slag to flush until the hole is raked out. After adding the hot metal, it is advisable to hold the initial slag in the furnace as long as possible to allow it to attain its maximum temperature and fluidity. When the slag level is at the top of the banks, the flush hole should be opened and usually the slag will be run off in about 30 min. After about an hour, the foaming slag settles and the bath boils on some of the remaining ore. The metal exposed during the ore boil, being much higher in carbon, is usually darker in color than that in the lime boil.

When the hot metal is added to an ore heat, the silicon, manganese, and phosphorus in the metal react with the ore and oxides present to form SiO_2, MnO, and P_2O_5. These oxides rise to the surface of the metal and with the iron oxides form the initial slag on the heat. After the slag has formed and the elements have been largely eliminated from the bath, the ore begins to react with the carbon in the iron to form CO gas. It is the evolution of this gas that causes the slag to rise in a foam and necessitates a flush-off at the proper time.

A typical analysis of a flush slag is as follows:

	Per cent		Per cent
SiO_2	25	Fe_2O_3	5
CaO	15	MnO	15
FeO	30	P_2O_5	3

The lime-silica ratio as seen from the foregoing percentages shows the slag to be predominantly acid in character. It is also interesting to note that as a result of the high FeO and MnO content this slag is often charged in the blast furnace to recover the elements from their oxides.

The Lime Boil.—After the ore boil ceases, the CO_2 gas resulting from the decomposition of the limestone rising through the metal is decomposed by iron and carbon to form CO. This rising gas forms a boiling action which is called the "lime boil." Neither slag nor metal actually boils, but lumps of lime are released from the bottom and float to the top in the slag.

As the lime rises, it combines with the silica in the slag to form a complex slag known as a monticellite type ($CaO \cdot RO \cdot SiO_2$—the RO representing MnO, FeO, Al_2O_3, etc.). During the latter part of the lime boil, as the lime dissolves in the slag, it decomposes the monticellites, releasing the RO group, and forms dicalcium silicate, $2CaO \cdot SiO_2$. If a dicalcium silicate coating is formed on the undissolved lumps of lime, it becomes difficult to get these lumps into solution. Fluor spar additions soften the coating and permit the lime to dissolve. If a white ring is noted around lumps of lime in a fractured slag sample, it is likely that the lime will be difficult to get into solution and spar must be used early in the heat. This condition is particularly evident in the slags of high MnO content.

As more lime rises, the silica is neutralized by the formation of dicalcium silicate, and the additional lime combines with the P_2O_5 in the slag to form tricalcium phosphate, $3CaO \cdot P_2O_5$. From this point on, any further addition of lime going into solution will combine with the iron oxides to form calcium ferrites, of which dicalcium ferrite is probably the most prevalent. These three steps that lime takes in combining with the silica, phosphorus pentoxide, and the iron oxides and the order of their occurrence

are particularly important with respect to the working period of the heat. This significance is emphasized in a later discussion.

Working the Heat.—A heat of basic open-hearth steel should be worked, with the product in mind, as quickly as possible to the correct carbon analysis with the phosphorus and sulfur reduced to the desired grade of steel. The following information is in general the accepted practice, but peculiarities of individual plants may alter the procedure somewhat.

Full-killed Steels.—These steels should be tapped with as low an oxygen content of the bath as possible. This can be governed by two factors: (1) as mild an oxidizing slag as possible and (2) as high a tapping carbon as possible to finish within the specified carbon range.

The first condition is the harder to control and until recent years slag control has been rather neglected from an operating standpoint. A mildly oxidizing slag can be obtained by working a heat under a 2:1 lime silica ratio until about an hour before tapping when the lime content is increased to give a lime-silica ratio of 2.4:2.6. Under normal furnace conditions of deoxidation this slag does not prevent a phosphorus reversion; neither does it give sufficient lime to the slag to increase the ferrites excessively.

Ore is added to the heat to reduce the carbon content of the bath. The amount of carbon removed depends on the size of the ore, the time at which the ore addition is made, and the temperature of the metal at the time of its addition. If the slag is lumpy and difficult to get into solution, an addition of small-sized ore will help shape up the slag although the effected carbon drop will not be so great as when the addition consists of large lumps of ore which sink through the slag and react directly on the metal. Ore additions to the heat are more effective if made when the lime silica ratio of the slag is under 2.3. The cooler the bath temperature, the more carbon will be reduced from a given ore addition. When the temperature of the bath is excessive and the carbon content very high, it is usually considered good practice to add large amounts of ore at one time to save the ore and also to reduce the temperature of the bath sufficiently to prevent excessive erosion of the furnace hearth.

If during the working period of the heat the slag shapes up with too low a lime-silica ratio (1.5:1), delays usually result, apparently owing to the fact that acid slags reflect too much of the

heat from the flame. The low ratio slags also cause the slag to foam badly on ore additions. With exceedingly basic slags, the lime boil is retarded, heat is reflected to the roof causing undue burning of the silica roof brick, and eventually a slag is produced with a high iron content.

The final ore addition should be made to a heat so that there is plenty of time for the ore to work out of the slag before the deoxidizers are added. A lumpy slag may physically trap some ore; and, as the temperature of the bath is increased at the end of the heat, the slag becomes thinner and ore is released to the bath and the steel is overoxidized.

The second factor affecting the oxygen content of the steel is the tapping carbon. As the oxygen content increases, the carbon content decreases. This relationship is noticeable between 0.20 and 0.11 carbon and becomes very pronounced below 0.11 carbon. As a result of this relationship, it becomes difficult to make quality steels from a cleanliness viewpoint when making killed steels that tap under about 0.10 carbon.

In basic slags two oxides of iron, FeO and Fe_2O_3, are always found with the ferrous oxide, FeO, predominating. The Fe_2O_3 is formed by the oxidizing gases reacting with FeO at the slag gas surface according to the equation

$$4FeO + O_2 = 2Fe_2O_3$$

The Fe_2O_3 is carried to the slag-metal surface by diffusion or convection currents in the slag or by the boiling action produced by the lime boil and carbon oxidation, and there is either reduced to FeO by the reaction, with iron from the bath, as

$$Fe_2O_3 + Fe = 3FeO$$

or is reduced by carbon, partly or completely, as

$$Fe_2O_3 + 3C = 3CO + 2Fe$$
$$Fe_2O_3 + C = CO + 2FeO$$

Part of the FeO released is dissolved in the steel, some is dissolved by the slag, and the cycle started over again. The FeO is, therefore, called the "oxygen carrier" of the process. The foregoing cycle in which the iron oxide is being continually enriched in oxygen in the top layer of the slag and losing it to

the metalloids and iron at the metal surface is the principal method by which impurities are removed from the bath.

It is at this juncture that the excess lime above that necessary for the formation of the dicalcium silicate and the tricalcium phosphate becomes an important factor. This excess lime in the slag combines with some of the Fe_2O_3 to form dicalcium ferrite according to the following reaction:

$$2CaO + Fe_2O_3 = 2CaO \cdot Fe_2O_3$$

As a result of this combination, the above mentioned oxygen cycle is broken by partly and temporarily removing Fe_2O_3. With all factors remaining fairly constant, there would be a rapid rise in Fe_2O_3 content and a corresponding decrease in FeO. Thus, if the lime goes into solution at a fairly rapid rate, the carbon drop would be very noticeably decreased, owing, of course, to the lack of oxygen transfer from the gas to the metal.

The viscosity of the slag affects the foregoing cycle of reactions because the more viscous the slag, the more difficult the diffusion of the Fe_2O_3 through the slag layer and the slower the removal of impurities from the bath. On the other hand, the more fluid the slag, the faster the FeO will diffuse from the slag back into the metal, a condition highly undesirable. Hence, the first helper attempts to have his slag of a creamy consistency during the finishing stages of the heat.

During the lime boil, a sample of steel is taken from the furnace and sent to the laboratory to determine the alloy contamination of the bath. The elements determined are usually copper, nickel, and molybdenum. A second sample is then taken to determine the carbon content of the bath. This may be determined in several ways. Probably the oldest method is by reading the fractured surface of a quenched sample. The method is as follows: A test is taken by inserting a long-handled spoon in the hole in the door and after coating it well with slag for insulation, dipping it into the steel, and pouring the contents into a small rectangular cast-iron mold. The sample is then cooled in water and fractured to show a cross section. An experienced furnace man can fairly accurately determine the carbon content by the appearance of the grains and blowholes. Another more accurate method for determining carbon is by the carbometer or other makes of apparatus that operate on the electrical conductivity

principle. The combustion method used by the chemist is the most accurate of all but the determination consumes too much time to make it adaptable to control work.

A sample for the determination of phosphorus and sulfur is sent to the laboratory shortly after the alloy sample. At the same time, a slag sample is poured into a shallow cup or pan about 4 in. in diameter and 1 in. deep and is allowed to cool. This sample is used in the estimation of the lime-silica ratio by inspection. The rate of change of the lime-silica ratio is important in working the heat. The slag pan or mold should have a bottom that has been roughened either by sandblasting or pickling so that certain characteristics of the sample pertaining to the bottom of the slag cakes are not destroyed.

If the lime-silica ratio as observed is too high to allow proper carbon reduction, additions of ore must be made. If the operator thinks that the bath will have too low a lime-silica ratio when tapping carbon content is reached, he should partly adjust this condition by adding lime before making the first ore addition so that the ore will help put the added lime into solution. Enough ore is then added to "break its back" or lower the carbon content to such a point that by the time all the lime has boiled off the bottom, only a slight addition of ore, or none at all if possible, will be required to reach the tapping carbon after the desired slag, phosphorus, and sulfur content, and temperature of the heat have been obtained. If any molybdenum is to be added to the steel, it is usually added at a carbon content about 10 to 15 points above the tapping carbon.

One of the most important duties of a first helper is the control of bath and roof temperature throughout the working of a heat. During the early stages of the heat, this is usually done by watching the roof temperature and slag characteristics. The ability to judge roof temperature is a great asset to the first helper. In the later stages of the heat, more accurate methods of temperature measurement are required. Two of the most practical methods of temperature determination are the spoon test and the rod cut test. The spoon test consists in well slagging a spoon, filling it with metal, and observing the amount of frozen metal that remains in the spoon as it is slowly poured out. Since slag viscosity and carbon content affect this test very greatly, the rod cut test appears to be the more practical of the two.

The rod cut test consists in immersing a steel rod of a given carbon content quickly in the bath so that it will not become coated with slag and moving it slowly back and forth while held in a horizontal plane. The metal boils on the rod. After this boiling action has subsided, the rod is withdrawn and the temperature noted as follows: on a very cold heat the rod will have collected steel; on a cold heat the rod will have been cut off to a long point; on a hot heat the end of the rod will be cut off square; while on a very hot heat the cut will be concave and there will be nicks in the rod in the slag area.

Tapping the Heat.—The last several points of carbon drop are used in preparing the heat for its final slag condition and tapping temperature. When the desired carbon content is reached, deoxidizers or "block" are added to the heat to remove the oxygen content and arrest the carbon drop until a combustion determination for carbon can be made by the chemist. A 4,000-lb., 15 per cent silicon, pig block should normally arrest the carbon drop for 15 min. in a 200-ton heat. Where the carbometer is used for carbon determinations, little or no blocking is necessary as this method of determination requires only a few minutes.

A good deoxidizer will produce deoxidation products that are very liquid at bath temperature and will coalesce and float to the surface. Where large furnace additions of weak deoxidizers, such as manganese and chrome, are necessary, owing to the specifications, they must be preceded by a strong deoxidizer such as silicon. Probably the two deoxidizers most commonly used are 15 per cent silicon pig and silicomanganese.

Two factors should be considered in making furnace additions. The first is the effect of the addition on phosphorus reversion. Of the usual deoxidizers used, the order of their ability to cause a reversion of phosphorus from the slag to the bath is as follows: (1) silicon, (2) silicomanganese, (3) 80 per cent manganese, (4) spiegel.

The other factor has to do with the ability of the addition to penetrate the slag and enter the bath. In general, it can be said that all additions should be large enough to penetrate the slag and directly enter the bath. In cases where the addition is small in size or light in weight, it is found desirable to moisten the addition before adding to the bath. This wetting causes a slight

explosion which removes the slag directly under the addition and allows it to drop into the metal.

Some additions such as ferrochrome are preheated before adding so that it will collect less slag and hence melt more rapidly in the bath.

Semikilled Steels.—This type of steel is worked similar to killed steels with the exception of a lower lime-silica ratio, about 2.2. However, when it is necessary to work sulfur, a more basic slag must be carried. As semikilled steels are deoxidized in the ladle, there is less chance of a phosphorus reversion than when blocking in the furnace, and the lower lime-silica ratio used in this instance results in the following savings:

1. The manganese residual is at its highest point at a 2.2 lime-silica ratio and a greater manganese efficiency is obtained.
2. Iron losses are low on this type of slag because of its low iron content.
3. A saving in fluxes.

Rimmed Steel.—This type of steel must be worked to give a high enough oxygen content at tap to ensure a good rimming action in the molds. The higher the tapping carbon, the more oxidizing the slag must be to produce the desired rimming action. When a tapping carbon is above 0.19 per cent, it is difficult to obtain sufficient oxygen content in the steel to produce a good rimming action in the mold, and artificial methods must be used to produce an ingot with the proper skin, by either bottom pouring or by additions of oxides to the molds, ladle, or bath to produce the desired ingot.

Tapping Operations.—When the heat is ready to tap, the second helper removes the clay plug from the rear of the taphole and rakes out the dolomite with which the hole was filled. A 20-ft. length of ¼-in. pipe is attached to an oxygen supply and the end of the pipe ignited by heating it in a hole provided in the back of the furnace. As the remaining crust in the front of the hole is burned out by the oxygen supplied through the rod, the metal flows from the furnace through the spout to a ladle set directly behind the furnace. If difficulty is experienced in getting a good-sized stream running into the ladle, a 1¾-in. square bar is driven into the taphole from the front of the furnace through the hole in the middle door. The center of the ladle is usually set a little to one side of the center of the pouring spout to give a

swirling action to the metal entering the ladle. Ladle additions should be of egg-size material in order to ensure rapid melting, and they should be added before any slag comes from the furnace to prevent a high alloy loss and a possible phosphorus reversion. Coal is sometimes added to the ladle to recarburize the heat when the carbon content has dropped slightly lower than necessary before tapping. This should be added first and allowed to burn off before adding silicon and manganese.

If aluminum is to be added, it is usually put in after the other additions have been made. Aluminum is added to killed steels to further the deoxidation and to control grain size of the steel.

A notch in the top of the ladle at one side allows the excess slag to overflow down a trough into a slag pot placed at the side of the ladle. The size of the ladle is such that it will just hold the metal and enough slag to form a blanket that prevents oxidation of the metal.

Deoxidizers and Alloys.—Table 1-III shows the efficiencies of deoxidizers and alloys utilized in the production of basic open-hearth steels. In general, it may be said that those alloying elements which are easily oxidized are added in the ladle or to the furnace just before tapping in order to avoid expensive losses as much as possible. Those elements which are not oxidized under steelmaking conditions are usually added any time after the heat is melted. Some of the alloying elements are used as deoxidizers as well as alloying elements in the finished steel, but different grades are usually used for the two different purposes.

The losses on molybdenum, nickel, and copper are not losses from oxidation but are mechanical losses.

Some of the alloys listed are used more often in making steel by the electric process than by open-hearth methods since the steels in which they are present are high-quality, special alloy steels. These include ferrovanadium, ferrotitanium, and ferrotungsten. In addition, several metallic elements, principally titanium, tungsten, and cobalt, are used as alloying additions in induction and electric furnace practice.

Ferroalloys.—A ferroalloy may be defined as "iron so rich in some element other than carbon that it is used as a means of introducing that element into iron or steel." Ferroalloys are added for three principal purposes: (1) to impart superior properties (strength, corrosion resistance, etc.) to the finished steel

(ferrochromium), (2) for their beneficial effect on the steel through their action on impurities in the steel (ferromanganese, by converting FeS to MnS), and (3) for their deoxidizing, degasifying, or scavenging effects on the steel (titanium). Of course, a ferroalloy may deoxidize the steel, have a beneficial effect on the impurities, and still be added in sufficient quantities to act as an

TABLE 1-III.—EFFICIENCIES OF DEOXIDIZERS AND ALLOYS ON BASIC OPEN-HEARTH HEATS

Material	Approximate alloy content	Furnace	Ladle
15% ferrosilicon, pig	15% Si	Si–40%	Never
50% ferrosilicon	50% Si	Never	Si–70%
75% ferrosilicon	75% Si	Never	Si–70%
85% ferrosilicon	85% Si	Never	Si–70%
Silicomanganese	70% Mn–2% C	Si–40%; Mn–70%	Never
Low carbon ferromanganese	82% Mn–0.75% C	Mn–70%	75–80%
Medium carbon ferromanganese	84% Mn–1.5% C	Mn–70%	75–80%
Regular carbon ferromanganese	80% Mn–6% C	Mn–70%	75–80%
Ferrophosphorus	22% P	Never	60%
Ferrochrome (low carbon)	70% Cr–0.04% C	Cr–70%	80%
Ferrochrome (medium carbon)	70% Cr–2.0% C	Cr–70%	80%
Ferrochrome (high carbon)	70% Cr–5.0% C	Cr–70%	80%
Ferrovanadium	35% V	Never	50%
Ferromolybdenum	60% Mo	98%	Never
Molybdenum salts	40% Mo	98%	Never
Electrolytic nickel	99.5% Ni	99%	Never
Copper	99.5% Cu	99%	Never

alloying element. Most of the ferroalloys used are products of the electric furnace. A few of those containing only small amounts of alloying element are produced in the blast furnace as a result of special operation.

It is of interest to note that the United States possesses very few ores sufficiently high in content of the various alloying elements for them to be readily transformed into the standard grades of ferroalloys. Molybdenum is practically the only

alloying element for which there is sufficient high-grade accessible ore in the country to supply the needs of the iron and steel industry.

Spiegeleisen or Speigel.[1]—Spiegeleisen or speigel is an alloy of iron and manganese used in Bessemer and basic open-hearth practice. The term is applied to those commercial alloys containing up to about 30 per cent manganese. Spiegeleisen is frequently used with scrap and pig iron in the open-hearth charge to raise the manganese content and to aid in cleaning up the bath. In Bessemer practice it is added to the steel after the blow to recarburize and bring the manganese within specifications.

The commercial grades of spiegeleisen usually fall within the following chemical range: 16 to 28 per cent manganese, 5.00 to 6.50 per cent carbon, 1.00 to 6.00 per cent silicon, 0.15 per cent maximum phosphorus, and 0.05 per cent maximum sulfur.

Ferromanganese.—Ferromanganese is an iron-manganese alloy containing more than 30 per cent manganese. Manganese is used as a deoxidizer and desulfurizer in the production of nearly all grades of steel and as an alloying element to assist in the production of a fine-grain structure and enhance physical strength and ductility. It is used for these purposes in all grades of steel whether intended for castings, forgings, or rolled products. The most commonly used grade of ferromanganese is termed "standard ferromanganese" which has a typical composition as follows: 78 to 82 per cent manganese, 7.50 per cent maximum carbon, 1.00 per cent maximum silicon, 0.35 per cent phosphorus, 0.05 per cent sulfur. Three other grades of ferromanganese are available. The first of these grades is known as "low carbon ferromanganese" which is used for adding relatively large amounts of manganese to low carbon steel. This particular grade is also used as a deoxidizer and scavenger in those grades of steel where low carbon and low silicon are necessary.

The typical grades of low carbon ferromanganese have an analysis range as follows: 80 to 85 per cent manganese, 1.00 per cent maximum silicon, 0.10 to 0.50 per cent carbon.

The second grade of ferromanganese is known as "medium carbon ferromanganese" which is used where relatively large

[1] Data on all ferroalloys were obtained from the "National Metals Handbook," 1936 ed., and from "Steel Products Manual," Sec. 1, American Iron and Steel Institute, 1937.

amounts of manganese are specified. This particular grade has a typical analysis range as follows: 80 to 85 per cent manganese, 1.50 per cent silicon, 0.75 to 1.50 per cent carbon.

The third grade is known as "low phosphorus ferromanganese," which is used for adding manganese to acid open-hearth steel and to other kinds of steel in which the phosphorus content must be kept to a minimum. The typical analysis of this grade is as follows: 78 to 82 per cent manganese, 5.00 per cent maximum silicon, 0.10 per cent maximum phosphorus, 5.50 to 6.50 per cent carbon.

Ferrosilicon.—Ferrosilicon is an alloy of iron and silicon, used in making silicon additions in the manufacture of open-hearth steel. In the basic open-hearth process it is used as a deoxidizer and scavenger prior to the use of more expensive alloys. In addition, it is used to prevent oxidation while holding the bath of steel for chemical determinations. High silicon ferroalloys are used in the manufacture of steel sheets or strips for the electrical industry. Ferrosilicon is also used in the manufacture of steels in which the silicon is used as an alloying element.

Many different grades of ferrosilicon are produced. The use of the different grades is dependent upon the purpose for which they are intended. The accompanying table gives the composition of the commercial grades of ferrosilicon. All these grades

Grade	Silicon	Carbon	Phosphorus	Sulfur
15% ferrosilicon.....	14-20%	1.00% max.	0.05% max.	0.04% max.
50% ferrosilicon.....	42-52%			
75% ferrosilicon.....	70-82%			
90% ferrosilicon.....	88-95%			

are furnished in crushed or lump form for ladle and furnace additions.

Silicomanganese.—When both silicon and manganese are desired as alloying elements or when silicon is not objectionable in making low carbon manganese steel, this ferroalloy is often used. It is also an excellent double-deoxidizer and is often used in small amounts on that account. Four different grades are obtainable, of the following approximate composition in percentage:

	Grade 1, %	Grade 2, %	Grade 3, %	Grade 4, %
Manganese	65-70	65-70	65-70	65-70
Silicon	20-25	16-20	14-18	12-14
Carbon	Max. 1.00	Max. 2.00	Max. 2.5	Max. 3.0

All grades are furnished in lump or crushed form.

Ferrochromium.—Ferrochromium is an alloy of iron and chromium, used for the introduction of chromium into steel. Chromium exerts its influence in bringing about a marked change in the properties of steel that is subjected to heat-treatment after rolling or forging, increases the hardness, increases the resistance to shock, imparts high tensile strength with increased ductility, and has the ability when added in sufficient amounts to produce high resistance to corrosion and oxidation. There are several different commercial grades of ferrochromium. The high carbon grade has a typical analysis as follows: 60 to 75 per cent chromium, 4.00 to 8.00 per cent carbon, silicon in percentages as specified. The low carbon grade has a typical analysis range as follows: 60 to 75 per cent chromium, 1.00 to 2.00 per cent carbon, silicon per cent as specified.

Ferrovanadium.—Ferrovanadium is an alloy of iron and vanadium, used in steelmaking principally for its alloying qualities, after deoxidation has been effected by less costly deoxidizers. Vanadium is added to steel for its benefits in imparting fine grain size, improved tensile strength without loss of ductility, and a marked increase in the elastic limit, yield point, and impact strength. The commercial grades of ferrovanadium have a typical analysis range as follows: 30 to 45 per cent vanadium, 0.20 to 3.00 per cent carbon, 1.50 to 8.00 per cent silicon, 0.250 per cent maximum phosphorus, 0.300 per cent maximum sulfur, 2.00 per cent maximum aluminum.

Ferrotungsten.—Ferrotungsten is an alloy of iron and tungsten, used principally in the manufacture of high-speed tool steels, tungsten magnet steels, in many hot-work tool and die steels, and in some heat-resisting steels. It is used for its property of imparting strength and hardness to alloy steel at high temperatures.

A typical analysis is as follows: 75.00 to 85.00 per cent tungsten, 0.75 per cent maximum carbon, 0.06 per cent maximum phos-

phorus, 1.00 per cent maximum silicon, 1.00 per cent maximum manganese. This alloy has a melting point between 3275 and 3450°F. and is used in sizes of from 1 in. down.

Ferrozirconium.—This alloy is a combination of iron and zirconium, used as a deoxidizer and scavenger of steel. Its tendency is to eliminate oxygen and nitrogen, as well as non-metallic inclusions in the bath, and in some cases to control the grain size of the steel.

For steels of high silicon content an alloy containing 12 to 15 per cent zirconium, 39 to 43 per cent silicon, 0.20 per cent maximum carbon is used. For steels with low silicon content the typical analysis used is as follows: 35 to 40 per cent zirconium, 47 to 52 per cent silicon, 0.50 per cent maximum carbon.

Ferrocolumbium.—Ferrocolumbium is an alloy of iron and columbium which finds its principal use in the manufacture of different grades of stainless and heat-resisting steels. Columbium is also used as an inhibitor of intergranular corrosion in high chromium and high chromium nickel steels.

The typical commercial analysis is as follows: 50 to 60 per cent columbium, 7.00 per cent silicon, 0.50 per cent maximum carbon.

Ferromolybdenum.—This alloy of iron and molybdenum is used in making additions of molybdenum in the manufacture of open-hearth and electric furnace steels. Molybdenum, as an individual alloying element, enhances most of the physical properties of the steel to which it has been added. It is, however, nearly always used in combination with one or more other alloying elements. The typical analysis of the commercial grade of ferromolybdenum is as follows: 50 to 60 per cent molybdenum, 2.50 per cent maximum carbon, 0.25 per cent maximum sulfur, 0.10 per cent maximum phosphorus.

In addition to the above grade there is also a low-carbon ferromolybdenum grade which is used when making additions of molybdenum to low carbon steel. It has an analysis range typical of the foregoing grade, with the exception that the carbon ranges to a maximum of 0.25 per cent.

Ferrotitanium.—Titanium is added to steel in several forms. For use as a scavenger and deoxidizer ferro-carbon-titanium is employed, and practically no titanium is left in the finished steel. The high carbon grade contains 17 per cent titanium, 7.5 per cent carbon, 2.5 per cent silicon and 1.00 per cent aluminum. When

titanium is desired as an alloying element, one of several low carbon grades is used, the compositions of which follow.

	Grade 1	Grade 2	Grade 3
Titanium	25	15-20	25
Silicon	. . .	15-20	Under 3.0
Aluminum	6.0	Under 1.0	Under 3.0
Carbon	. . .	Under 0.5	Under 0.1

The first grade is made by the aluminothermic process while the other two are electric furnace products.

Ferrophosphorus.—Ferrophosphorus is an alloy of iron and phosphorus, used for the addition of phosphorus to some grades of steel. It is commercially available in two grades, the one containing 17 to 19 per cent phosphorus; while the other contains 23 to 25 per cent phosphorus.

Typical Calculations on an Open-hearth Heat.

Specification: 0.40/0.50C, 1.30/1.60Mn, 0.04 under P and S, 0.20/0.30 Si.

Furnace Deoxidizers: Silicomanganese (70 per cent Mn, 15 per cent Si, 2 per cent C).

Ferromanganese (80 per cent Mn, 6 per cent C).

Ladle Deoxidizer: Ferrosilicon (50 per cent Si).

Charge: 275,000 lb. scrap
175,000 lb. iron
450,000 lb. total

Oxidation loss = 10 per cent of charged weight.

$$450{,}000 - 0.10 \times 450{,}000 = 405{,}000 \text{ lb. of steel tapped}$$

Residual Manganese: 0.21 per cent.

Furnace Additions: 4,000 lb. silicomanganese block (by experience).

4,000 × 0.70 = 2,800 lb. manganese obtained from silicomanganese. At 70 per cent efficiency and 4,050,000 lb. of steel,

$$\frac{2{,}800 \times 0.70}{405{,}000} = 0.48 \text{ per cent Mn to bath from silicomanganese}$$

$$4{,}000 \times 0.15 = 600 \text{ lb. Si obtained from silicomanganese}$$

At 40 per cent efficiency and 405,000 lb. of steel

$$\frac{600 \times 0.40}{405{,}000} = 0.06 \text{ per cent Si to bath from silicomanganese}$$

To determine manganese addition adding all manganese in the furnace:

0.21 per cent from residual manganese
0.48 per cent from silicomanganese
0.69 per cent manganese present

1.45 per cent (specific aim) − 0.69 per cent = 0.76 per cent to be obtained from 80 per cent ferromanganese.

Using an alloy containing 80 per cent Mn and of 70 per cent efficiency:

$$\frac{0.0076 \times 405{,}000}{0.80 \times 0.70 \text{ (eff.)}} = 5{,}496 \text{ lb. ferromanganese to be added}$$

To determine ferrosilicon addition to ladle:

0.25 per cent − 0.06 per cent (from silicomanganese)
= 0.19 per cent Si required

Using an alloy containing 50 per cent Si and at 70 per cent efficiency:

$$\frac{0.0019 \times 405{,}000}{0.50 \times 0.70 \text{ (eff.)}} = 2{,}190 \text{ lb. ferrosilicon to be added to ladle}$$

To determine tapping carbon:

From 4,000 lb. silicomanganese is obtained
4,000 × 0.02 = 80 lb. C.
From 5,496 lb. ferromanganese is obtained
5,496 × 0.06 = 330 lb. C.
Total......... 410 lb. C.

$$\frac{410}{405{,}000} = 0.10 \text{ per cent carbon pickup from furnace additions}$$

Specification of 0.45 per cent C − 0.10 per cent = 0.35 per cent carbon for tapping

Stationary Practice.—The following graphic description of making a 100-ton heat of basic open-hearth steel is taken from a

paper published by J. L. Keats and C. H. Herty, Jr.[1] and is fairly typical of stationary furnace operation on plain carbon heats from pig and scrap. The elimination of the impurities from the metal can be followed in Fig. 11-III and the changes in slag composition in Fig. 12-III. The analyses of the raw materials and the finished steel are given in Table 2-III.

Charging of the furnace was started at 8:23 A.M. with the introduction of 26,000 lb of limestone. The charging of the scrap was started at 9:06 and continued until 9:20, 175,000 lb. of scrap being added during this time. No cold pig was charged. Melting of the scrap was started at once and no further additions were made until 11:34. During this time, oxidation of the scrap occurred with the formation of FeO. At the same time, the scrap was absorbing sulfur from the furnace gases.

By the end of two hours, the scrap had melted sufficiently to allow the introduction of 23,000 lb. of molten pig iron in door 2 without scoring the bottom. During the period between the charging of the scrap and the hot metal addition, two chemical reactions take place: (1) oxidation of the scrap while it is melting, FeO being the principal oxide formed, and (2) the calcination of part of the limestone. When all of the hot metal is added, part of the scrap and all of the limestone are submerged in the bath. Oxidation of the exposed mounds of scrap proceeds until sufficient scrap has melted to raise the level of the liquid enough to cover all of the solid material.

TABLE 2-III.—ANALYSES OF RAW MATERIALS AND FINISHED STEEL

	C, %	Mn, %	P, %	S, %	Si, %
Pig iron	4.14	1.37	0.362	0.059	1.17
Scrap	0.67	0.84	0.025	0.033	0.149
Ferromanganese	6.44	76.4	0.25	0.86	
Ferrisilicon	0.337	......	0.04		
Finished steel	0.372	0.608	0.0138	0.0209	0.081

During the melting period, the calcination of the limestone results in the formation of a large amount of CO_2, which bubbles up through the bath and slag and causes a heavy boiling action. Hence, the period covered by this action is called the "lime boil," although neither the metal nor the slag actually boils. Some of

[1] KEATS and HERTY, *Trans. A.I.M.E.*, **73**, 1079 (1926).

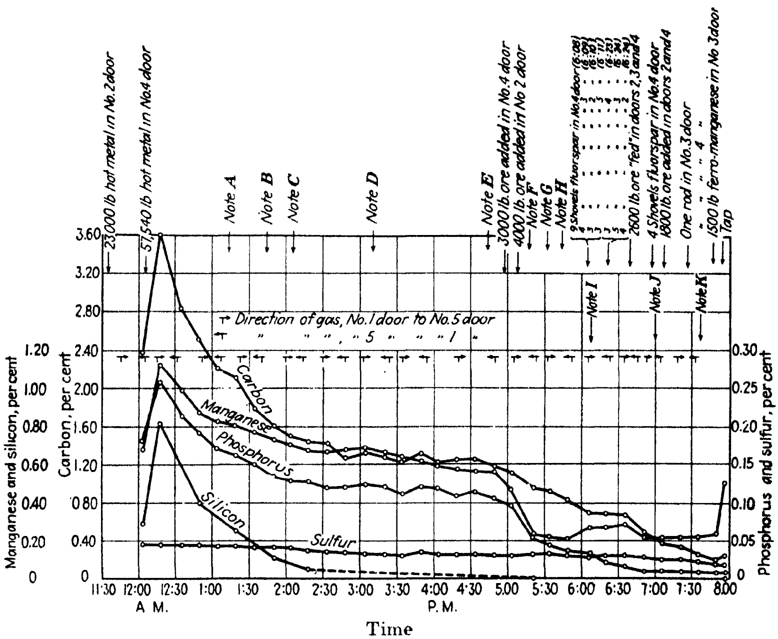


FIG. 11-III.—Variations in composition of metal bath from hot-metal addition to tapping. (*From Keats and Herty.*)

NOTES TO ACCOMPANY FIG. 11-III

NOTE A: Metal boiled vigorously around and on the outer edge of the mounds of pasty semimolten scrap. Some lime lumps floated to the surface along the front wall. A collection of kish[1] still hung on the front bank at door 4, remaining from the last ladle of metal that was poured in at that door.

NOTE B: A vigorous boiling action continued on the mound of scrap at door 2.

NOTE C: At this time the slag had quite an appreciable amount of lime floating on its entire surface. The heat had the appearance of melting high in carbon, *i.e.*, the slag contained hard sharp-edged lumps of lime and the metal was dark in color.

NOTE D: Lime boiling up over the entire bath. Several lumps of scrap still above the level of the bath. The furnace was being run at a low temperature and the lime of the slag was softening somewhat. The fluid portion of the slag was getting thicker.

[1] Kish is residue from molten pig iron.

the CO_2 thus formed is subsequently reduced by iron and carbon to CO, and the oxidation of carbon itself results in CO. Gases from these reactions all contribute to the boiling action of the slag. As the scrap melts, it releases the lime which it previously held down by its weight and the lime rises to the surface in chunks and is slowly dissolved in the slag.

As noted above, the initial melting period produces a large amount of iron oxide by oxidation of the exposed scrap. This FeO combines with some calcined limestone from the bottom and with dolomite from the furnace banks to produce an initial slag high in lime and iron oxide. When the molten pig iron is added, the initial slag reacts with the metalloids in the pig very rapidly, silicon and manganese being removed quickly (Fig. 11-III). The lime boil has a pronounced effect on this purification since the boiling action of the bath agitates it violently and mixes the upper and hotter layers of metal with the colder lower layers. This agitation also brings the slag into intimate contact with a large amount of metal and hastens the transfer of the impurities to the slag.

The silicon is rapidly removed by oxidation to SiO_2 and rises into the slag where it combines with lime to form principally

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NOTE E: Lime was still boiling up in door 3. Both ends were rather quiet, appearing as though the lime were all up in each end. The furnace and bath were quite cool and the slag was very viscous. The steam pressure (producers) was raised at this point to increase the volume of gas, thus raising the temperature and thereby hastening the boiling up of the last of the lime.

NOTE F: The slag dissolved the ore at once and vigorous action took place throughout the entire bath.

NOTE G: The temperature of the bath was rising; the slag was more fluid; and the general action of the bath more open.

NOTE H: The slag was still frothing from ore addition.

NOTE I: The lime was still boiling up at door 3. The slag was of good consistency.

NOTE J: Lime boil ceased and lime was apparently all up. The slag was a little heavy.

NOTE K: Slag still showed the effects of the two recent ore additions. The rods stirred through the heat served to settle the frothing.

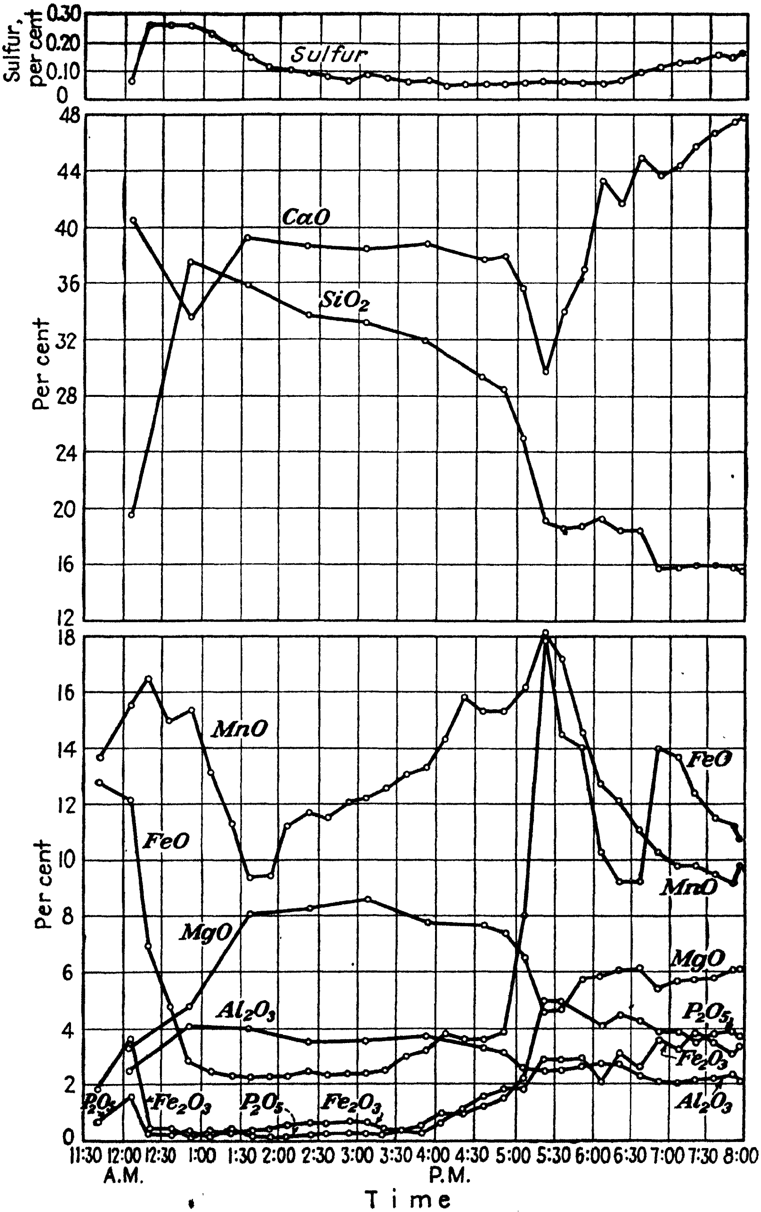


FIG. 12-III.—Variations in slag composition from hot-metal addition to tapping. (*From Keats and Herty.*)

dicalcium silicate, $2CaO \cdot SiO_2$. The manganese is removed by oxidation to MnO and probably dissolves in the dicalcium silicate. The removal of sulfur cannot be easily controlled, principally because the scrap and slag absorb sulfur from the furnace gases, if producer gas is used as fuel. A high manganese content in the metal favors the removal of sulfur due to the reaction of sulfur with manganese producing MnS. A high basicity of the slag favors the retention of sulfur as CaS in the slag. Also, some sulfur is oxidized to SO_2 and escapes from the bath as a gas. Figure 11-III shows the elimination to be slow and steady, the rate of elimination increasing somewhat toward the end of the heat.

The phosphorus in the bath is oxidized to P_2O_5 and combines principally with FeO to form $3FeO \cdot P_2O_5$. As the lime rises into the slag, the FeO is replaced by CaO, forming a stable tricalcium phosphate, $3CaO \cdot P_2O_5$. The carbon is removed rather slowly after the initial drop and the attempt is made at all times to keep the carbon from being eliminated to the desired point before the other impurities have been eliminated. The carbon in the bath serves to protect it from excessive oxidation. Hence the melter always tries to remove the phosphorus before the carbon.

A proper slag is of the utmost importance in the production of good basic steel as the impurities are removed as oxides and retained in the slag. In order to prevent the phosphorus in the slag from returning to the metal in the later stages of the process, it is necessary to carry a considerable excess of lime in the slag in order to form the stable tricalcium phosphate. This lime rises from the bottom during the lime boil and brings about the necessary state of high basicity in the slag. During the melting stage, the rapid elimination of silicon and manganese by reaction with FeO in the slag causes a sharp decrease in the FeO content of the slag and a corresponding increase in SiO_2 and MnO (see Fig. 12-III). This slag is only weakly basic and causes severe erosion of the basic banks of the furnace. The liberation of lime from the furnace bottom and the erosion of the banks increase the basicity of the slag to the desired point.

To return to the description of the heat pictured in Figs. 11-III and 12-III, by 3:00 P.M., the elimination of the impurities had slowed down very much, and the slag was thickening rapidly

owing to the solution of lime in it. The lime boil was in full swing, but the elimination of the impurities was not proceeding very rapidly due to the thickness of the slag and the low FeO content. The bath and slag temperatures were on the low side and the carbon content in the bath was rather high (about 1.3 per cent).

As soon as the lime was all up at the ends of the furnace, the foregoing condition was corrected by the addition of ore and the raising of the temperature of the furnace by more frequent reversals of the gas and air. The effect of the ore additions on the bath and slag can be seen in Figs. 11-III and 12-III. The large increase in FeO content of the slag increased its oxidizing power markedly and the impurities in the bath decreased rapidly in amount. The ore additions caused the vigorous frothing action of the bath due to the rapid reactions, and the rising temperature, together with the ore addition, caused the increase in fluidity of the slag. This procedure is called "oring down" the heat. The amount of ore added depends upon the carbon content of the heat and upon the amount of carbon desired when the heat is tapped.

Between 6:00 and 6:30, fluor spar was added to thin the slag to the desired consistency, as a heavy viscous slag makes for slow removal of the impurities in the bath. Ore and spar were then added, the ore to remove the last of the impurities and the spar to keep the consistency of the slag at the desired point. The lime boil did not entirely cease until 7:00 and the frothing of the bath after that time was due to the ore additions. This froth was settled by stirring steel rods through the slag.

In preparing the heat for tapping, the melter should have the heat worked down until the impurities in the bath are at, or preferably below, the required values. He should be certain that the slag has the desired consistency and composition and that the temperature of the heat is right for tapping. In the heat under discussion, ferromanganese was added to the bath just before tapping partly to deoxidize the heat. It was tapped almost immediately into the ladle and 700 lb. of ferrosilicon was added to the ladle during tapping to further the deoxidation and 420 lb. of coal was added at the same time to raise the carbon to the desired point. Two pounds of aluminum was added during teeming and served to complete the deoxidation.

The foregoing description is fairly typical of stationary-furnace operation, but several important variations in practice may be found in use at many plants.

Open-hearth Slags.—As pointed out earlier in the chapter, the open-hearth slag system is complex in nature, but the furnace operator is interested mainly in the two components of a basic slag (which he must obtain on killed heats to prevent a phosphorus reversion): lime, CaO, and silica, SiO_2. The type of slag is generally spoken of in terms of its lime-silica ratio; an acid slag has a lime-silica ratio below 2.3 after correcting for P_2O_5. Above this ratio the slag is termed basic. The formation of an open-hearth slag consists in putting into solution the desired amount of lime to neutralize the silica first and then enough excess lime to control the phosphorus and sulfur.

After the first lime has dissolved in the slag and all the silica has been satisfied as decalcium silicate, the dissolved excess lime forms tricalcium phosphate by a reaction with the phosphorus pentoxide. After all the P_2O_5 has been satisfied with lime, calcium ferrites are formed with the remaining lime and the iron oxides begin to increase rapidly.

The amount of limestone to be charged is governed by the amount of silicon and phosphorus in the charge. The higher the silicon and phosphorus content of the iron, the more lime must be charged to satisfy their oxides. Much less lime is required on flush heats where ore is charged than in scrap heats because much of the silica formed is run off before any limestone rises from the bottom.

Fluxes.—The fluxes most common in preparing basic open-hearth slags are fluor spar and burnt lime and sometimes roll scale. Fluor spar is basic in nature and contains about 3 to 5 per cent SiO_2, 10 to 12 per cent of iron and aluminum oxides, and at least 85 per cent calcium fluoride (CaF_2). When it is added to the bath, it breaks up into calcium and fluorine, the latter passing off as a gas. Sand is also used as a flux on a limy slag to retain iron oxide at a low value.

Slag Control.—The present trend in open-hearth practice is to charge the heat with a slightly deficient lime charge and by determining the lime-silica ratio and other slag characteristics at various stages of the heat, make adjustments with burnt lime and spar to obtain the correct type of slag at tap for the grade of

heat ordered. A method has been devised whereby, from the characteristics of a pancake sample, the lime-silica ratio and phosphorus and sulfur drop can be quickly determined. Slag pancake samples also enable the operator to work the heat under the fastest conditions so there will be no delay in shaping up the heat after the desired tapping carbon and temperature are reached.

Phosphorus cannot be removed from the steel until enough lime is supplied to form dicalcium silicate plus enough to form tricalcium phosphate, but then there must also be sufficient lime left in the slag to take care of the deoxidation products resulting from the block. The following reaction shows the chemistry of the phosphorus reversion in steel at tap:

$$4(3CaO \cdot P_2O_5) + 5Si = 2(6CaO \cdot P_2O_5) + 5SiO_2 + 4P$$

There is always a slight reversion of phosphorus to the steel on a killed heat, of at least 0.005 per cent with a basic slag of a 2.4+ lime-silica ratio. Iron charges containing from 0.200 to 0.500 per cent phosphorus do not greatly affect the phosphorus residual of the heat. In a case where the P_2O_5 content in the slag is high and heavy blocks are used on the heat, the slag is flattened out to such an extent that the bottom section of it must absorb all the deoxidation products and, unless a very large excess lime is carried in the slag, a phosphorus reversion is very likely to occur.

Sulfur removal in working the heat is usually a slow process partly because some fuels tend to give up sulfur to the bath. Conditions favorable for sulfur removal are (1) an excess lime to form a basic slag, (2) good bath temperature, and (3) an active slag.

In the first condition the excess lime should not be present too early as the slag will become saturated with ferrites. This tends to lower its ability to absorb sulfur. If the lime is present too early, the bath will have too long a period to absorb sulfur from the flame. The elimination of sulfur is shown by the following reactions:

$$FeS + CaO = CaS + FeO$$

also,

$$FeS + CaO + C = CaS + CO + Fe$$

These reactions are favored by heat; hence, a high bath temperature will tend to increase their speed. In addition, the carbon content should be sufficiently high to produce agitation of the bath. On low carbon heats, where the carbon content has dropped below 0.08 per cent and the sulfur residual is too high to meet the specification, an artificial action must be given to the slag by reboiling with pig iron, spiegel, or manganese but, as this will slow up the heat time by at least 20 min., it is far better to work sulfur above 0.10 carbon range with a medium thin slag.

Slag Tests.—The chemical analysis of slags may often be misleading unless great care is taken to separate any solids such as pieces of lime. A thorough sampling procedure is used. Microscopic studies have been made by preparing thin sections of slags and studying them under a petrographic microscope. These analyses take more time than the furnace operator can allow in working a heat, but they have been very beneficial in developing a simple method of determining slag characteristics from the pancake sample.

The pancake slag tests are of great value if studied in connection with previous and subsequent samples and the steel bath itself. To do this the operator should start about the middle of the lime boil and take samples at various times until the heat is tapped, laying them in sequence on the floor so that they may be observed while working the heat.

The first slags, which are low in lime-silica ratio, show a gray wrinkled top. As the heat progresses, the wrinkles get fewer and the top changes to a black shiny appearance with an increase in lime and iron oxides. The bottom of these slags shows an iridescent shine like water. After a 2.3 lime-silica ratio is reached, the bottom turns dull. This is a most important part of the sequence to watch for, as the slag is then basic in nature, and sulfur elimination from the steel becomes noticeable. Phosphorus reversion will not occur after this point. Caution should be taken that the bottom of the sampling pan is roughened so there will be no misinterpretation in the change in appearance of the bottom of the pancake. As more lime goes into solution, the bottom remains dull, and the top starts to get dull until finally a point is reached where a dull gray top and a dull bottom result. As the iron content of the slag increases, the top begins to show a crystalline film around the edge of the top of the sample

which indicates a total iron content of about 13 per cent. At about 15 per cent total iron the crystalline film covers about one-third of the surface, at 17 per cent about one-half of the top surface, at 19 per cent about three-fourths of the top surface, and at 21 per cent total iron the entire top of the sample is covered with the crystalline film.

The photographs that appear on the following pages were taken at different stages of a heat and may be used as a guide in learning the use of slag pancake samples in working the heat.

The chemical characteristics of a basic open-hearth slag may be determined with sufficient accuracy for control purposes from a calculation of the corrected lime to silica ratio, commonly called the V value. This value is a ratio of the bases to the acids in which the total lime is corrected for the P_2O_5 content on the assumption that all the P_2O_5 in the slag is combined as $3CaO \cdot P_2O_5$ and, further, that the principal constituent is SiO_2. The formula for this calculation is as follows:

$$V = \frac{\text{Per cent CaO} - 1.19 \text{ per cent } P_2O_5}{\text{Per cent } SiO_2}$$

This value, which is a measure of slag basicity, may be calculated in other ways from the reported analysis. The principal ways, including the foregoing, are

1. Lime-silica ratio, per cent $\frac{CaO}{SiO_2}$.
2. Corrected ratio, $\frac{CaO}{SiO_2 + 0.634P_2O_5}$.
3. Excess lime, $CaO - 1.86SiO_2 - 1.19P_2O_5$.

In addition to the foregoing determination, a method is also used to express the iron oxide content of the slag. This function is of value in that it furnishes an approximate figure of the oxidizing power of the slag. Thus, with a given temperature, known slag basicity, and a measure of the iron oxide content, the properties of a slag can be accurately predicted. The principal methods of reporting the FeO in the slag are

1. Total Fe reported as FeO.
2. Ferrous oxide reported as FeO.
3. FeO plus Fe_2O_3.

GROUP I

Frost Flower Slags
$V = 1$ to $1+$

Characteristics:

Fracture—glassy
Bottom—shiny

Analysis, per cent

SiO_2	= 31.2
CaO	= 36.7
P_2O_5	= 2.0
MnO	= 14.3
FeO	= 4.8
Fe_2O_3	= 1.4

$V = 1.10$

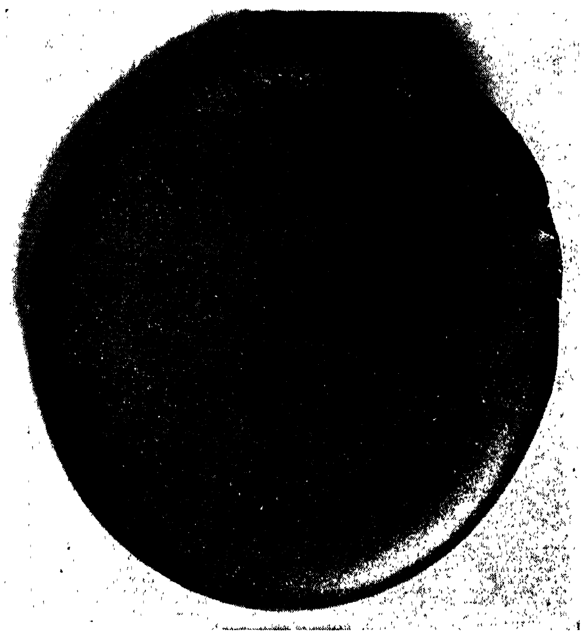


FIG. 13-III.

This is a very early slag rarely seen on the heat but is prevalent on heats that have had brickwork and quantities of silica roof brick left in the furnace which have become melted in the slag. They have the crystalline top of a high iron basic slag but differ in the fact that they have a glassy fracture and shiny bottom.

GROUP II

Composition: Monticellite: $CaO \cdot RO \cdot SiO_2$

Creased Slags

$V = 1.2$ to 1.4

Characteristics:

- High phosphorus residual
- Phosphorus reversion
- Sulfur pickup
- Fracture—black and porous
- Bottom—shiny

Analysis, per cent

SiO_2	=	21.7
CaO	=	35.3
P_2O_5	=	3.1
MnO	=	9.4
FeO	=	10.9
Fe_2O_3	=	2.1
V	=	1.4

FIG. 14-III.

These slags have a mild oxidizing action because the FeO is tied up in the monticellite. The creasing is influenced mostly by the MnO in the slag.

GROUP III

Composition: Dicalcium silicate: $2CaO \cdot SiO_2$

Furrowed Slags

V = 1.6 to 2.15

Characteristics:

Lower phosphorus residual
Phosphorus reversion
Sulfur pickup
Strong oxidizing action
Fracture—stony and brown
Bottom—shiny

Analysis, per cent

SiO_2	=	18.8
CaO	=	39.1
P_2O_5	=	4.7
MnO	=	14.1
FeO	=	8.4
Fe_2O_3	=	3.0

V = 1.78

FIG. 15-III.

In this type of slag the creases have become wider and now appear as furrows on the top of the slag. Like the creased slags, the furrows are connected with the MnO; the higher the MnO and the lower the lime-silica ratio, the deeper the furrows. Ore additions are most economical at this time because of the strong oxidizing action of this type of slag.

GROUP IV

Composition: Dicalcium silicate: $2CaO \cdot SiO_2$ and tricalcium phosphate: $3CaO \cdot P_2O_5$ plus excess lime, CaO

Intermediate Slags

V = 2.15 to 2.4

Characteristics:

- Less phosphorus residual
- Slight phosphorus reversion
- Slight sulfur drop
- Very mild oxidizing action
- Low Fe content
- Low MnO content
- Top—flat, smooth, and shiny black
- Fracture—stony; increase in glittering particles with increasing Fe content
- Bottom—shiny

Analysis, per cent

SiO_2	=	19.1
CaO	=	46.7
P_2O_5	=	4.6
MnO	=	5.0
FeO	=	8.1
Fe_2O_3	=	1.9
V	=	2.15

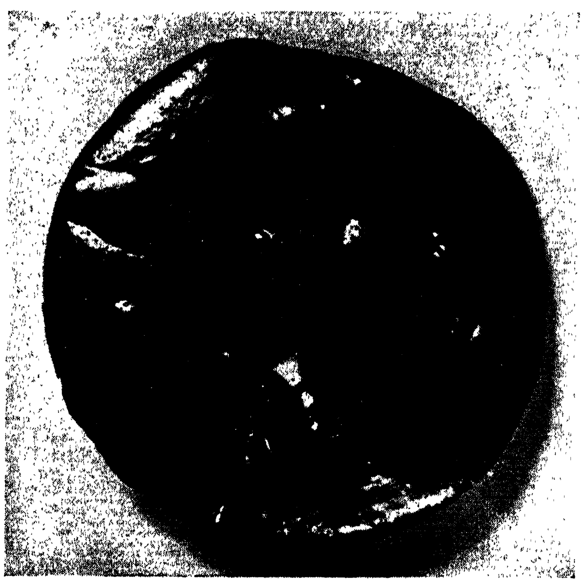


Fig. 16-III.

A phosphorus reversion will occur if a heat is blocked with ferrosilicon on this type of slag.

GROUP V

Composition: Dicalcium silicate: $2CaO{\cdot}SiO_2$; tricalcium phosphate: $3CaO{\cdot}P_2O_5$; dicalcium ferrite: $2CaO{\cdot}Fe_2O_3$

Basic Slags

V = over 2.4

Characteristics:

Very low phosphorus residual
No phosphorus reversion
Rapid sulfur drop
Very strongly oxidizing
High Fe content
Low Mn residual
Top—black to dull
Fracture—striated structure—increase in glittering particles with increasing Fe
Bottom—dull

Analysis, per cent

SiO_2	= 14.6
CaO	= 44.2
P_2O_5	= 2.8
MnO	= 11.1
FeO	= 11.5
Fe_2O_3	= 3.5
V	= 2.8

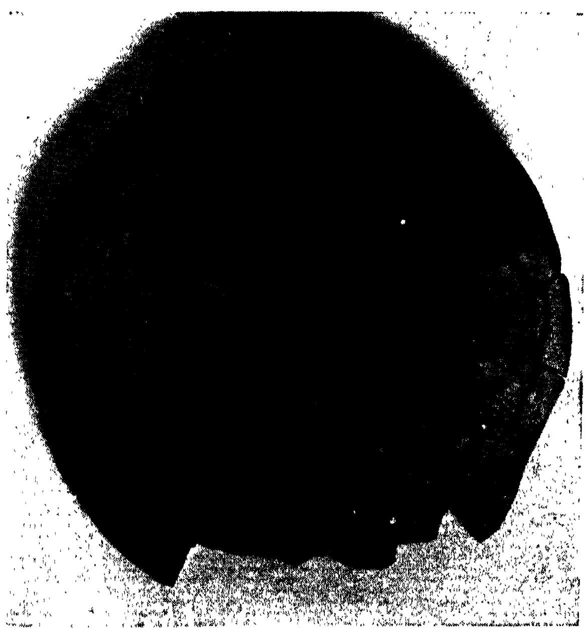


FIG. 17-III.

GROUP V

Composition: Dicalcium silicate: $2CaO \cdot SiO_2$; tricalcium phosphate: $3CaO \cdot P_2O_5$; dicalcium ferrite: $2CaO\ Fe_2O_3$

Basic Slags

V = over 2.4

Characteristics:

- Very low phosphorus residual
- No phosphorus reversion
- Rapid sulfur drop
- Very strongly oxidizing
- High Fe content
- Low Mn residual
- Top—completely covered with crystalline film
- Fracture—striated with many glittering particles
- Bottom—dull

Analysis, per cent

SiO_2	= 13.2
CaO	= 44.1
P_2O_5	= 3.3
MnO	= 3.1
FeO	= 28.4
Fe_2O_3	= 9.6

V = 3.04

FIG. 18-III.

GROUP V

Composition: Dicalcium silicate: $2CaO \cdot SiO_2$; tricalcium phosphate: $3CaO \cdot P_2O_5$; dicalcium ferrite: $2CaO \cdot Fe_2O_3$

Basic Slags

V = over 2.4

Characteristics:

- Very low phosphorus residual
- No phosphorus reversion
- Rapid sulfur drop
- Very strongly oxidizing
- High Fe content
- Low Mn residual
- Top—black with spider-web pattern
- Fracture—striated
- Bottom—dull

Analysis, per cent

SiO_2	=	13.4
CaO	=	45.5
P_2O_5	=	5.5
MnO	=	7.1
FeO	=	16.8
Fe_2O_3	=	7.1
V	=	2.91

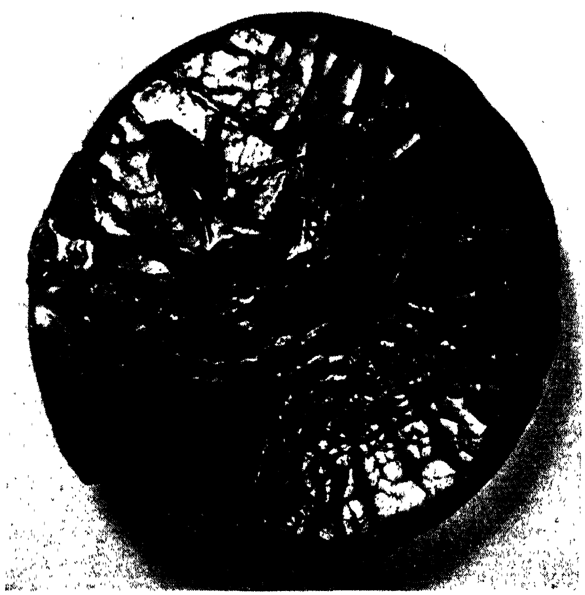


FIG. 19-III.

The black spider-web top seen on this sample is produced by the presence of high P_2O_5 content in the slag.

Typical Alloy Practice.—The following is a detailed description of the making of a heat of chrome-nickel alloy steel in the basic open-hearth furnace. It is a typical example of the methods used in making steels of lower alloy content by the pig and scrap process. In some cases hot metal additions are made instead of cold ones, but the usual practice is about as here described. Most of the automotive and aviation alloy steels are made by this method, or modifications of it.

A heat of steel was to be made by the scrap and pig process with the following restricted analysis scheduled to the open hearth: 0.33/0.36 carbon, 0.70/0.80 manganese, 0.04 maximum sulfur and phosphorus, 0.15/0.30 silicon, 1.00/1.50 nickel, and 0.55/0.70 chromium. First, 16,000 lb. of some light scrap was charged on the repaired bottom of the furnace at 12:30 P.M.; 15,000 lb. of raw limestone and 4,000 lb. of burnt lime were next charged, on top of which was placed the remainder of the scrap consisting of 32,000 lb. of rails and 63,000 lb. of miscellaneous nickel-bearing crop ends. The fuel was turned on the furnace and the scrap melted down. At 4:45 P.M., 96,000 lb. of cold pig iron was charged. The pig soon melted and ran until the whole bath was leveled off. This molten iron then slowly dissolved the lower carbon scrap charge and a few pieces of the limestone began to come up around the edge of the bath. This limestone blanket insulated the metal from the heat and the boiling ceased. At such a time, the furnace should be watched closely to prevent melting the brickwork and something should be done to hasten the action of the bath and prevent burning the furnace. If the carbon content is high enough to permit, some ore may be added; if not, the lime may be cut or dissolved with fluor spar.

A test was taken and fractured. The carbon was estimated to be 1.25 per cent and the nickel determined chemically to be 0.89 per cent. A box of ore (about 3,500 lb.) was added at 11.15 P.M. The ore softened the lime blanket and permitted more heat to penetrate into the bath, causing the balance of the limestone to come up. Since the nickel is desired to finish at about 1.25 per cent, therefore (1.25, desired nickel $-$0.89, preliminary) $\times$ 208,000 (charged weight) $\div$ 100 $=$ 749 lb. nickel to be added. This amount of nickel was added at 11:45 P.M. while the first ore charge was working through the bath.

At 12:30 A.M. another fracture test was taken. Carbon was estimated to be 0.80 per cent, so 2,000 lb. more of ore was added. When this ore action ceased, the fracture test showed about 0.30 per cent carbon. This test piece was then checked chemically for carbon, manganese, sulfur, phosphorus, nickel, and chromium. The results, reported at 2:05 A.M., were 0.278 per cent C, 0.26 per cent Mn, 0.017 per cent P, 0.030 per cent S, 1.20 per cent Ni, and 0.09 per cent Cr. A reboil of 1,500 lb. of spiegeleisen was added to hold the carbon content of the bath at a constant value while final shaping up of the heat was progressing. A box of burnt lime was added to help stiffen the slag which had become a little too fluid through the effects of the ore. Since the nickel analysis showed 1.20 per cent, enough nickel must be added to bring the nickel-free additions such as manganese, silicon pig, ferrochrome, spiegel iron, and iron derived from the iron ore addition, if any, up to the desired nickel content, plus the five points shortage in the bath. This was calculated to require 150 lb. and this amount was added.

The slag being in shape and the sulfur, phosphorus, and temperature being at the desired values, the heat was judged ready to go ahead. A test was taken for carbon and manganese check. Two thousand pounds of silicon pig was added at 2:45 A.M. to check the action of the bath; the ferrochrome (2,000 lb.) was next added and finally the ferromanganese (1,600 lb.) at 3:08 A.M. When this was melted, the heat was tapped at 3:20 A.M. The coal (210 lb.), ferrosilicon (900 lb.), and aluminum (75 lb.) were added to the ladle as the heat ran from the furnace.

The ferromanganese contained 80 per cent manganese and 6 per cent carbon, and the ferrochromium contained 70 per cent chromium and 5 per cent carbon. Both manganese and chromium were added to the furnace to get them uniformly alloyed with the bath and because of the impracticability of melting such large quantities of substances in the ladle. Some allowance must be made for oxidation losses. The melter estimates these losses with the aid of his experience and the appearance of the bath.

Estimating the efficiency of the ferrochrome to be 70 per cent and aiming at a finished content of 0.61 per cent chrome in the finished heat, the ferrochrome additions were calculated by the following equation:

$$\frac{0.0061 - 0.0009 \text{ (residual)} \times 210{,}000}{0.70 \times 0.70} = 2{,}228 \text{ lb. ferrochrome}$$

Similarly, the ferromanganese necessary was calculated to be 1,600 lb.

The melter carried the heat to 0.36 per cent carbon total by taking the bath content plus the carbon contained in the ferromanganese, ferrochrome, and making up the balance from anthracite, calculating an efficiency of 60 per cent for the coal. The total heat (210,000 lb.) finished with the following analysis: 0.345 per cent C, 0.73 per cent Mn, 0.16 per cent P, 0.028 per cent S, 1.26 per cent Ni, and 0.61 per cent Cr.

Teeming the Heat.—Three general methods are used in transferring the metal from the ladle into the ingot molds: (1) direct top pouring, (2) pouring with a tun dish, and (3) bottom pouring. In all the methods used, the procedure must be carefully controlled to give the best results. The temperature of the metal, the speed of pouring the ingot, the method of pouring, and the size, shape, and temperature of the mold must all be taken into account in producing the desired quality of steel for a definite use.

In top pouring, the ladle is suspended directly over the first ingot of the train of molds and the stopper opened. The rate of pouring is carefully regulated by controlling the stopper opening and the size of the nozzle. If aluminum is added to the mold, the required amount is added, either in liquid or solid form, when the mold is about one-third full. When the mold is full, or nearly so, the stopper is closed and either the ladle moved over the next mold in the train or the train of molds moved until the next ingot is under the ladle. If the ladle is supported by a traveling electric crane, the ladle is moved, but if a stationary jib crane is used, a hydraulic pusher moves the train of molds the required distance.

This method of pouring is used for all classes of steel, killed, and rimming steel, and is used with all types of ingot molds, big-end-up, big-end-down, and either with or without a hot top. In pouring rimming steel, the mold is never filled completely as the evolution of gas increases the volume of the metal enough to cause it to "grow" or push up in the mold somewhat. In case the heat does not rim properly, the difficulty is sometimes partly corrected by jarring the ingots up and down during solidification. This is carried out by means of a movable platform

upon which the car of molds rests, the platform being lifted and dropped by means of a cam arrangement under it. This method seems to increase the thickness of the sound skin of metal on the rimmed ingot even when rimming normally. In making rimmed steel, the ingot is sometimes capped to keep the steel from growing in the mold. A heavy plate is placed upon the steel and wedged in place by a heavy bar which is passed through two "ears" in the ingot mold.

Top pouring has the advantage of being the cheapest and most direct method of transferring the metal from the ladle to the molds as it does not require auxiliary equipment. For these reasons it is the most used method, particularly where the highest quality is not wanted. All killed steels, semikilled steels, and most rimmed steels are top-poured.

The method has, however, several serious disadvantages. The metal at the bottom of the ladle is under a tremendous pressure due to the weight of the metal above it, and the stream leaving the nozzle has a high velocity. This causes splashing in the mold—a serious drawback since the splashings freeze on the mold walls and cause imperfections on the surface of the rolled products. Furthermore, the metal entering the first mold has the highest velocity and at the same time is the most fluid since it is at the highest temperature. When the last ingot is filled, the metal leaving the nozzle has the lowest velocity since there is little pressure behind it; at the same time, it has the greatest viscosity since the contents of the ladle have cooled considerably in the meantime. This state of affairs is obviously not what it should be since, in order that all the molds may be filled alike, the most fluid metal should be poured the slowest, and the least fluid with the highest velocity. In top pouring, this difficulty can be partly avoided by opening the stopper only partly at the beginning and opening it wider and wider as the teeming progresses. By this means, the volume of metal poured per minute can be equalized but the velocity of the stream cannot, while the partly opened stopper undergoes very severe erosion from the metal.

In order to conquer the difficulty of controlling the velocity of the stream of metal entering the mold and its effect upon splashing, the tun dish was introduced. This is a shallow steel receptacle, either square or rectangular in cross section and lined with

refractory brick. The dish has either a circular hole at each end of the bottom or a hole in each corner, depending upon whether two or four ingots are being poured at once. If four ingots are being poured simultaneously, the molds are grouped in fours on the pouring floor and are not placed on cars. The tun dish is supported horizontally over the group so that each hole in the bottom of the dish is over the center of a mold. The ladle is

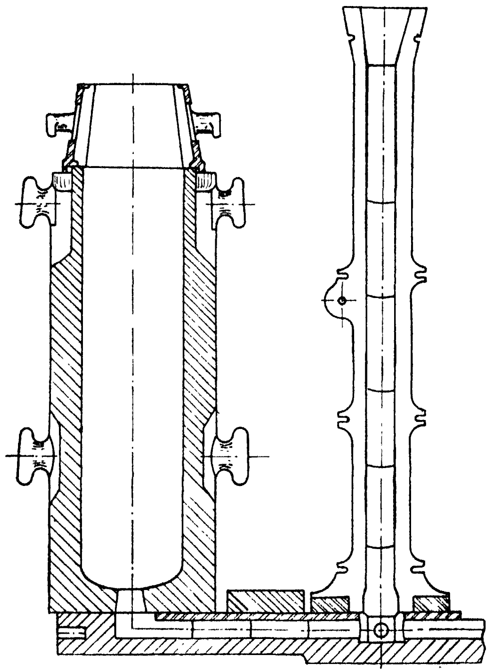


FIG. 20-III.—Arrangement for bottom pouring. (*After Reagan.*)

spotted over the tun dish and the four molds filled at once by keeping the dish full of metal and allowing it to run out of the holes in the bottom into the molds.

This method of pouring eliminates the high velocity of the stream leaving the ladle nozzle since the only pressure on the metal is that of the amount in the tun dish.[1] The entire heat can, therefore, be poured with the same velocity. The actual velocity is, of course, reduced considerably below that encoun-

[1] HRUSKA, J. H., Finishing the Heat of Steel, *Blast Furnace Steel Plant*, **20** (Sept. 1932) (continued in subsequent issues).

tered in pouring directly from the ladle and, consequently, splashing and its attendant difficulties are reduced to a very small figure by this method. In addition, the holes in the tun dish are eroded by the metal and grow larger as the heat is teemed. This allows more metal to flow toward the end of the heat when the fluidity of the metal is less. The method has, however, the disadvantages of being more expensive than top pouring and requiring a slightly higher teeming temperature since the metal is subject to more cooling during the pouring procedure than with top pouring. The oxidation of the metal is also greater. Owing to the above factors, pouring with the tun dish is usually reserved for killed steels where quality is of some importance. Hence, big-end-up hot-top molds are usually used with this method.

The third method of pouring, called "bottom pouring," consists in introducing the metal into the mold through the bottom. This type of pouring is more expensive than the others and is limited to high-quality killed steel manufacture and is usually used in filling big-end-up, hot-top molds.

Figure 20-III shows the ordinary setup of mold and runner for this type of practice, which is carried out on the pouring floor.[1] The molds are set on a heavy casting, the size and shape of which depend upon the number of ingots being poured from the central runner. As many as 8 or 10 ingots can be conveniently poured at once from a 100-ton ladle, in which case the base plate is circular, the molds are equally spaced around the circumference, and the vertical runner is placed in the center. The vertical and horizontal sections of the runner are lined with the best quality of refractory and all connections are made metal tight. The runner is usually made about 2 ft. higher than the top of the molds so that there will be a definite pressure on the metal in the molds. The heat is teemed by spotting the ladle nozzle over the top of the central runner and allowing its contents to flow down through the runner, the horizontal channels, and up into the molds in succession.

The factors mentioned above with regard to general pouring precautions should be watched very carefully when using this pouring procedure. If the rate of pouring is too high, circumferential cracks appear in the ingots, usually near the hot top.

[1] Reagan, W. J., *Trans. A.I.M.E.*, Iron and Steel Division, **90**, 45 (1930).

On the other hand, if the pouring speed is too low, an excessive amount of SiO_2 is washed from the runner bricks by the stream of metal and carried into the mold.

This method of pouring has the advantage of filling the mold without agitation or splashing of the metal. In addition, the chance for oxidation during the teeming operation is much less than with other methods. In fact, this method of pouring, when carefully operated, undoubtedly produces the best steel. Its disadvantages are that it is expensive and, therefore, limited in use, and that contamination of the metal with silica is a continual danger. When only one ingot is being poured from the runner, a combination of top and bottom pouring is sometimes used, particularly for large forging ingots. Since the metal that enters the runner first is on top as the metal rises in the mold, it is subjected to the most cooling action and is, therefore, the coldest metal in the mold. Since the metal in the hot top should be the hottest and the last to solidify, this difficulty is often avoided by pouring the mold about three-quarters full from the bottom, quickly moving the ladle over the mold and completing the job by pouring directly into the mold. In this way, the metal in the top of the mold will be hot, since it is direct from the ladle.

Status of the Basic Open-hearth Process.—The basic open-hearth process is by far the predominant steelmaking process in use in this country today and seems likely to remain so for many years to come. Approximately 87 per cent of the steel made in the United States in 1942 was made by this process. The reasons for the predominance of this method are many. A few of them can be mentioned here.

In the first place, the process is adaptable to both large- and small-scale production. One-ton and 400-ton furnaces can be operated, but it is true that a 100-ton furnace is probably the most economical from a large-scale production standpoint. Also, it has a wide adaptability in the choice and proportions of raw materials charged. This is of very great importance since the scrap situation has become of such economic importance in this country.

Furthermore, the process is primarily one of refining and, for this reason, can utilize a wider range of pig and scrap compositions than any other. This is particularly true in regard to phosphorus. The basic open-hearth can refine ores of higher

phosphorus content than the Bessemer process can utilize and, since most of the ores in this country are not of Bessemer grade, the basic open-hearth process has enjoyed a tremendous advantage.

Finally, this process has been more intensively studied than any other, with regard to improvement in furnace design, steelmaking practice, and operating efficiency. This research work has led to notable savings in cost of operation, fuel consumption, and such great increases in quality that many operators now believe that as good a quality of steel can be produced in the basic as in the acid open-hearth furnace.

The reasons for the superiority of basic open-hearth over acid Bessemer steel can be summed up as follows:

1. The use of an oxidizing agent other than air and the external application of heat make the temperature of the bath independent of the purifying reactions. This factor allows much better control of the process.

2. The elimination of the impurities can be made to take place as gradually as is necessary and the bath and slag compositions, as well as the temperature, can be kept under control at all times.

3. The control of oxidation and deoxidation is much better in the open-hearth than in the Bessemer.

4. The procedure of blowing air directly through the bath in the Bessemer process leaves the metal with a much higher content of gases than does the basic open-hearth process. This gaseous content is difficult to remove before solidification and, if it is not done, the ingot contains blowholes which are sometimes the cause of much difficulty in the rolling mill and in subsequent fabrication operations.

Suggested Questions for Study and Class Discussion

1. What heating method made possible the development of the open-hearth process? Why is this method necessary?

2. What advantage does the open-hearth process possess over the Bessemer process? Are there any disadvantages? Explain the reason for the superiority of basic open-hearth steel over acid Bessemer steel.

3. Describe the basic open-hearth furnace construction.

4. Why are open-hearth furnaces built long, flat, and shallow?

5. Describe the construction and function of the reversing valves.

6. How is a basic bottom constructed?

7. List the types of fuels used in the open hearth. Which type of fuel is most desirable from an operating viewpoint? From a metallurgical viewpoint?

8. What is the purpose of the stacks? How is air introduced into the system?

9. What raw materials are charged into the furnace? Give the approximate analysis of pig iron used in the basic process.

10. What is the function of the slag in the basic process? How is it formed? How is it removed from the furnace and ladle? Give its approximate analysis.

11. How do viscosity and composition of the slag affect the working of the heat and how are they controlled?

12. Explain what is meant by reboil, lime boil, and ore boil.

13. Show the steps involved in making a normal heat of basic open-hearth steel including the charging sequence, and give the approximate time required for each step.

14. What are the most important chemical reactions that take place in the furnace and in the ladle during the making of a heat?

15. What are rimmed steel, semikilled, and killed steel? How are they made? What deoxidizers are used and at what step in the operation are they added? How is the grain size controlled?

16. How are ferroalloys added to open-hearth steel? List six. State in each case the purpose of the addition.

17. What is used to remove the impurities in the furnace? What elements are removed, in whole or in part, and in what sequence?

18. How is FeO introduced in the basic process? How is the concentration of FeO controlled?

19. How are phosphorus and sulfur removed in the basic operation? What is meant by phosphorus kickback?

20. If the first three C checks after melt down were 3.20, 3.15, and 3.14 per cent, what would you do to the heat?

21. *a.* Figuring on a 75 per cent efficiency from additions made to a heat, calculate the amount of ferromanganese required to meet the specification on the following heat:

Order:	0.10/0.12 C	0.40/0.60 Mn	0.04 P max.	0.055 S max.
Residual in bath:	0.10 C	0.15 Mn	0.016 P	0.035 S
Analysis of ferromanganese added:	5.0 C	80.0 Mn		
Size of heat:	100,000 lb.			

b. What would the tapping carbon have to be if the manganese specification were raised to 1.15 per cent, figuring on an 80 per cent efficiency on all additions?

CHAPTER IV

THE ACID OPEN-HEARTH PROCESS

The open-hearth process as developed by the Siemens brothers was carried out on an acid hearth and utilized pig and ore for the charge. Several years later the Martin brothers substituted scrap for part of the pig and thus hastened the process by lowering the carbon, manganese, and silicon contents of the total charge. The process as used in this country today is essentially a composite of the Siemens and Martin processes. The charge consists of pig and scrap, the scrap being usually more than 60 per cent of the charge. The elimination of carbon is hastened by judicious additions of ore, thereby saving much time.

The Furnace.—The acid furnace is constructed just like the basic furnace except for the bottom which is built up of silica sand. In addition, the acid furnace is usually considerably smaller than the basic, rarely exceeding 60 tons in capacity and more generally of the order of 20 to 40 tons.

In making bottom in the acid furnace, the taphole is set by lining the hole in the brickwork with ganister, plugging it with anthracite coal, and backing it with sand on the furnace side and with a clay plug on the outside. When the furnace is completely dried out, a thin layer of sandstone or granite chippings is spread over the bottom and banks and the temperature of the furnace increased until this material begins to fuse. A ¼-in. layer of silica sand is now spread evenly over the bottom and the furnace heated until the sand begins to fuse and glazes over. This process is repeated until the bottom and banks are built up to a foot or more in thickness. The glazed sand layers form a very hard, solid bottom. If the sand is too pure, trouble will be had in fusing it, since the melting point of pure SiO_2 is very high, 3142°F. If the sand contains too much impurity of lower melting point, the sand will fuse easily but will be worn away rapidly by the metal. A sand containing between 94 and 97 per cent SiO_2 is probably the best for such work, although physical characteristics and other factors must be taken into account.

When the bottom is made up, the hearth is filled about one-half full of acid slag which is melted and rabbled up on the banks to wash them down. This treatment serves to consolidate the bottom and make it impervious to the action of the metal. The furnace is now ready for charging.

The Acid Open-hearth Charge.—Since phosphorus and sulfur cannot be removed in the presence of an acid bottom and slag, the raw materials for the charge should be carefully selected so that the phosphorus and sulfur contents of the charge will be a little less than the values required in the finished steel. Neither phosphorus nor sulfur is removed and, since there is a loss of iron in the process, there is a slight increase in the amounts of these elements in the finished steel. There is also an increase in sulfur in the metal, owing to absorption from the gases, unless a gas unusually low in sulfur is used.

Specifications for acid open-hearth pig usually require a silicon content of under 2.0 per cent, manganese between 1.5 and 2.0 per cent, and phosphorus and sulfur below 0.03 per cent. The scrap used should be very carefully graded as to size and analysis to prevent high phosphorus and sulfur scrap from creeping in. Only the larger sizes of scrap are generally used in order to cut down the amount of FeO formed during the melting stage and also to be sure that all the scrap can be charged into the furnace at once. The silicon and manganese contents of the charge are desired fairly high in order to protect the carbon from oxidation during melting.

A thick layer of cold pig is usually charged on the bottom, followed by the scrap charge and the remainder of the pig in succession. The pig on the bottom helps to prevent the iron oxide formed by scrap oxidation from cutting the bottom, and the pig on top of the scrap cuts down the oxidation of the scrap during the same stage of the process.

Operation of the Furnace.—When the charging is completed, the gas and air are turned on full and the melting of the heat carried out as quickly as possible. This requires two to three hours, however, even for a 20-ton furnace. It is quite necessary to have the carbon content considerably above the required finishing value when the heat is melted, or it is impossible to work the heat correctly. If the heat melts down too low in carbon (owing to too low a silicon and manganese content in the charge

or to too severe oxidizing conditions during melting), the heat is pigged back with either pig iron or spiegeleisen. This is poor practice and is expensive owing to the time lost. The melter's log of a 20-ton acid heat is found on page 104. Although not all the data are given, the progress of the heat can be followed quite satisfactorily by studying the sequence of operations as noted in the log.

When the heat is completely melted, the temperature is allowed to rise for a while before any additions are made. During the melting period nearly all of the silicon and manganese are oxidized by the FeO formed by oxidation of the scrap. These oxides combine to form silicates of iron and manganese and make up the slag. Since the manganese and silicon serve to protect the carbon from oxidation, 0.60 to 0.80 per cent carbon is usually left in the bath.

The color and physical characteristics of the slag are also of considerable importance at this stage of the heat. If the slag is black or very dark, it means that its iron oxide content is too high and time should be allowed for it to lighten in color. With so high a FeO content in the slag, the carbon content of the bath is uncertain. The viscosity of the slag is also apt to be quite high at this time owing to the high SiO_2 content, and the diffusion of FeO into the metal will, therefore, be slow. Small amounts of lime are often added to improve the quality of the slag. The lime makes the slag more fluid by lowering the melting point of the mixture and also serves to displace FeO from the slag into the metal, since it is highly basic. If the FeO content of the slag is low enough but the viscosity is too high, the slag may be thinned with fluor spar.

After the bath is quite hot, a fracture test is taken by the melter to estimate the carbon content of the heat. From the results of the test, the experienced melter is able to judge the amount of ore necessary to reduce the carbon to the desired tapping point. This ore is added in two or three small doses and the carbon watched carefully by means of fracture tests after each addition. These additions cause a fairly vigorous boiling action due to carbon monoxide evolution and each boil is allowed to cease and a carbon test taken before more ore is added. During the oring down of the heat the slag gradually lightens in color, owing to the reduction in its FeO content.

Log of Acid Open-hearth Heat
(Carbon Casting Heat)

Time		Pounds
	Carbon scrap	7,500
	Pig iron	11,500
	Carbon scrap	9,300
	Carbon shavings	6,200
	Carbon shavings	4,000
	Total	38,500
3:00 A.M.	Started charging	
4:15	Charged 80% manganese	400
6:00	Finished charging	
8:00	Burners shifted every 20 min.	
8:30	Melted down	
	Test for C—0.79%, P—0.045%. Slag dark	
8:55	Test for C—0.74%	
9:10	Test for C—0.73%	
9:25	Test for C—0.70%	
9:30	Furnace down, oil off	
9:40	Furnace on (off 10 min.)	
9:50	Charged ore	200
10:10	Test for C—0.58%. Slag fracture green on melter's test	
10:15	Charged ore	200
10:40	Test for C—0.50%. Slag lighter in color	
10:55	Charged ore	100
11:10	Test for C—0.38%	
11:40	Test for C—0.32%	
12:15 P.M.	Test for C—0.25%. Heat being held for silicon reduction	
12:45	Test for C—0.25%. Slag light in color	
1:00	Test 0.03% silicon	
1:15	Test for C—0.21%	
	Charged lime	60
1:32	Test 0.03% silicon	
1:35	Charged 80% Mn	100
1:40	Test 0.09% silicon	
1:41	Hot test, 28 sec.	
1:56	Hot test, 27.5 sec.	
	Charged 50% silicon	230
2:06	Charged 80% manganese	330
2:09	Rabbled	
2:10	Hot test, 16 sec.	
2:11	Tapping test, C—0.25%. Slag fracture green on melter's test	
2:12	Tapped into ladle. Two pounds of aluminum added in the furnace	
2:17	Pouring in ladle 5 min. Held in ladle 4 min.	
2:19	Pouring	
	Spoon test for melt superintendent, quiet	
	Spoon test for laboratory, quiet	
2:30	Heat poured, skull on ladle	

Note: A green fracture of a cold slag sample gives the melter some indication that the FeO content is low.

The amount of ore to be added depends upon the judgment and experience of the melter and the grade of steel being made. If too much ore is added, the heat has to be pigged back with consequent loss of time. This practice also has been found to result in an inferior quality of steel due to inclusions in the finished steel. On the other hand, if too little ore is added, the carbon elimination will be too slow and time will also be lost. If the correct amount of ore is added, the heat will lose carbon rather rapidly to a point only a little above that desired for a finishing value. The remainder of the carbon should be eliminated slowly by means of the FeO already in the bath and slag in order to free the bath of excess oxide. The bath temperature is being raised throughout this portion of the operation.

As the carbon is slowly approaching the finishing value, the bath will increase in silicon content if the heat is handled correctly. This phenomenon is commonly designated as "condition" and is quite evident to the experienced melter. The ore boil is replaced by a slag surface practically flat with only occasional bubbles coming through it. In general, the slag is light in color when condition has been attained. The pickup in silicon from the slag is usually followed by fracture tests. Getting the heat in "condition" is necessary in producing high-quality steel, and the possibility of reaching it depends chiefly on the skill of the melter in adding the proper amounts of ore at the right time.

When the fracture test shows that the carbon is at the desired point, a test is sent to the laboratory for rapid carbon analysis. If this figure checks the melter's estimate and the heat is in "condition," a small amount of ferrosilicon is added to hold the carbon at the right value since carbon is not oxidized in the presence of excess silicon. The addition of the ferrosilicon at the correct time is of great importance. If added too soon, the carbon elimination will take too long and, if ore is added to speed this up, the condition of the bath will be ruined. If added too late (the carbon is lower than desired), the heat will have to be pigged back in order to finish at the required value and the quality of the steel suffers.

Assuming the bath to be in "condition," the temperature of the bath quite high, and the carbon at the desired value, the deoxidizers are added in the furnace and a few minutes (usually 15) allowed for the bath to free itself from oxides. Ladle addi-

tions are rarely made and the use of aluminum is not usual practice in making high-quality acid steel. The heat is tapped into the ladle at a temperature considerably higher than the desired teeming temperature and the heat held quiescent in the ladle for from 15 to 30 min. to allow the products of the deoxidation to enter the slag blanket that covers the metal. The ease with which this can be done in acid practice, without danger of detrimental contamination of the metal, accounts for the usual freedom of acid steel from nonmetallic inclusions.

In teeming acid steel for forging purposes, big-end-up hot-top ingots and bottom cast practice are usually used. Acid steel is expensive to make and is generally only used when high-quality or special alloy steels are needed. Hence, the utmost care is taken in producing good ingots. The increase in quality resulting from this practice more than justifies the added cost.

Chemistry of the Acid Open-hearth Process.—One reason often advanced to account for the superiority (real or fancied) of acid over basic open-hearth steel is that the acid process is inherently less complicated since purer raw materials must be used and no attempt is made to eliminate phosphorus and sulfur. That the acid process is less involved can be seen from the following discussion.

During the melting of the heat the silicon and manganese of the charge react with the FeO formed by the oxidation of the iron.

$$\mathrm{Si + 2FeO = SiO_2 + 2Fe}$$
$$\mathrm{Mn + FeO = MnO + Fe}$$

The oxides formed combine to make up the slag by reactions of which the following one is a type.

$$\mathrm{SiO_2 + MnO = MnO{\cdot}SiO_2}$$

In addition, some FeO combines with silica to form ferrous silicates. The type reaction is

$$\mathrm{FeO + SiO_2 = FeO{\cdot}SiO_2}$$

At the end of the melting stage the carbon begins to be eliminated by reaction with FeO.

$$\mathrm{C + FeO = CO + Fe}$$

The reason why the elimination of silicon and manganese occurs before the elimination of carbon is that the reactions leading to the elimination of manganese and silicon are exothermic (give off heat) and are, therefore, favored by the lower temperatures during the melting of the heat. When the bath is superheated before the ore addition, the carbon reaction is favored more and more since this reaction is endothermic (takes up heat) and consequently is favored by high temperatures. Furthermore, FeO will react with Si and Mn before it will with carbon and the carbon is, therefore, not oxidized rapidly until the silicon and manganese are nearly all gone.

The early elimination of manganese and silicon allows a fairly good slag to be formed almost as soon as the heat is melted. As stated above, this early slag is usually quite high in FeO and the amount can be reduced by allowing it to diffuse slowly into the metal or by displacing it with lime, according to the reaction.

$$FeO{\cdot}SiO_2 + CaO = CaO{\cdot}SiO_2 + FeO$$

Care should be taken in adding the lime to prevent it from fluxing the acid lining of the furnace.

When the ore is added to the bath, a vigorous boiling action occurs owing to the elimination of the carbon. The Fe_2O_3 in the ore is immediately reduced to FeO, which reacts with the carbon according to the equation given above. Uncombined FeO in the slag is oxidized at the upper surface of the slag to Fe_2O_3 by the furnace gases as follows:

$$4FeO + O_2 = 2Fe_2O_3$$

This Fe_2O_3 is carried to the metal surface by slag agitation and simple diffusion, as in the basic process, and reduced to FeO by reaction with iron.

$$Fe_2O_3 + Fe = 3FeO$$

By this means, the oxidizing gases are continually oxidizing the bath. This effect can be increased by keeping the viscosity of the slag down as diffusion is favored by high fluidity.

The slag in the acid process consists chiefly of SiO_2, MnO, and FeO. Small quantities of Fe_2O_3, CaO, Al_2O_3, etc., are also present but, with the exception of Fe_2O_3, are not important in

purifying the bath. A large part of the FeO is combined with silica, and this combined iron oxide will not diffuse into the metal and is not readily oxidized by the furnace gases. For a given total FeO content of the slag, there is much less FeO that can contribute to the oxidation of the bath than in the basic process. This accounts in part for the lower FeO concentration in the acid bath.

A typical slag composition at the "condition" point will be

	Per Cent
CaO	8.2
SiO_2	61.0
FeO	13.6
Al_2O_3	2.2
MnO	12.8

The percentage of FeO + MnO in the slag is automatically regulated since complex iron-manganese silicates will dissolve up to about 60 per cent SiO_2, the necessary amount over that obtained from the metal charge being taken from the furnace banks. Therefore, by closely regulating the amount of MnO in the slag (by regulating the Mn in the charge), the FeO can be closely controlled.

The amount of FeO dissolved in molten steel of a certain composition at a certain temperature and covered by a slag of a certain composition is approximately proportional to the FeO content of the slag (theoretically, exactly proportional). The distribution of the total FeO in the furnace between the bath and slag varies with the above conditions, the principal factor in the composition during the later stages of the heat being the carbon content.

When all the ore has been added and the heat is slowly approaching the desired point in carbon content, the rate of oxidation of carbon to CO is proportional to the amount of FeO and carbon present. As the oxidation of carbon proceeds, oxygen is required and this oxygen must come from FeO. The FeO dissolved in the metal is used first and its place taken by free FeO (uncombined with SiO_2) diffusing in from the slag. An approximate condition of equilibrium is finally set up between the FeO content of the bath and the carbon content, in which the FeO content reaches a minimum value consistent with the carbon content. Actual equilibrium is impossible of attainment

owing to the oxidizing influence of the furnace gases in furnishing FeO. This influence is small, however, since the free FeO concentration in the slag is quite low this late in the process. If the melter has added just the correct amount of ore at exactly the right time, the balance of the carbon elimination after the ore boil has ceased will take place at the expense of the FeO and reduce this component to a minimum value. At the same time, as the above equilibrium is approached, the carbon content of the bath will be at the desired value for tapping. It is obvious that considerable skill, experience, and judgment are required of the melter in order to arrive at this result.

When the above result has been attained, the bath will begin to pick up silicon by reduction from the slag, probably according to the equation

$$SiO_2 + 2C = Si + 2CO$$

This "condition," or pickup of silicon, indicates that the bath is pretty well deoxidized (free of FeO), since the presence of very much FeO in the bath would cause the oxidation of silicon to SiO_2. It is obvious that the less the amounts of deoxidizers that have to be used, the smaller the amount of oxide inclusions to be removed. This deoxidation of the acid bath before the final additions are made probably accounts for the fact that acid steel is, on the average, cleaner than basic steel. The slag can never be made actually neutral in nature, owing to the oxidizing effect of the furnace gases, but it can be made to be practically neutral.

The deoxidizers produce the same results as discussed in the basic process and the reaction will not be repeated here. They are usually added to the furnace and, since all the phosphorus is present in the metal, there are no dangers of phosphorus reversion as is true of the basic process.

Status of the Process.—The acid open-hearth process was the first open-hearth process to be introduced and developed in this country. It still produces a considerable tonnage. Since it requires pig iron very low in phosphorus and sulfur content and the great majority of ores in this country are not of the necessary quality, the basic process has far outstripped the acid process in point of production. It has also met serious competition from the electric process in recent years because the basic

electric process can take the same if not cheaper raw materials and turn out products that are equal if not superior in quality. Again, the recent advances in basic open-hearth practice have allowed the makers of basic steel, when making high-quality steel, practically to equal the quality of acid steel at a much lower cost. Finally the cost of the acid process is fairly high since it makes smaller batches than the basic, requires high-grade expensive raw materials, and requires a long time for melting and refining.

The term "quality" steel has been used in making comparisons. In reality, we should not say "quality" steel, for, after all, a quality steel for one purpose is not a quality steel for another. The acid furnace is used to produce, shall we say, steels that require acid melting practice to be of proper "quality." For example, steels that are required to have high physical properties taken transversely from forgings are peculiarly the product of acid furnaces.

About half of the acid open-hearth steel produced at the present time goes into the production of castings, the remainder into special products such as springs, bridge cables, and razor-blade stock, and a whole range of alloy steels. Only a very small tonnage of rimmed steel is made by this process, most of the production being killed steels of the plain carbon and alloy grades.

Suggested Questions for Study and Class Discussion

1. Describe the differences in construction between acid and basic open-hearth furnaces. Compare the compositions of the raw materials charged into both.

2. Give the approximate analyses of pig iron used in the acid and basic processes. Why is pig iron added in the molten condition to basic furnaces and in the solid condition to acid furnaces?

3. Describe the operation of the furnace in producing an acid open-hearth carbon steel heat.

4. How is the FeO introduced in the acid process? How is the concentration controlled? Why is there more FeO in the bath in the basic process as compared to the acid process even under similar slag oxide concentrations?

5. Why does the acid process fail to remove phosphorus and sulfur?

6. What is meant by silicon pickup and phosphorus kickback?

CHAPTER V

THE ELECTRIC FURNACE PROCESSES

William Siemens made the first attempt to melt steel electrically in 1878 when he conducted experiments on arc melting in a small crucible. His results were not particularly satisfactory, owing principally to mechanical and electrical troubles, but the principle was entirely correct. Experimentation was continued by many different investigators from about 1880 on, and a wide variety of furnace designs were introduced, using electricity for melting metal in practically every possible way.

Of the many types of electric furnaces introduced, only two have seemingly stood the test of time. The first is an arc furnace devised by Heroult about 1890 for the production of ferroalloys and subsequently developed and improved both mechanically and electrically to its present state of prominence in the electric melting field. The furnace was first put into production in this country in 1906 and was first used for the production of high-grade tool steels and other steels that were made at that time solely by the crucible process. At the present time the arc furnace is used to produce many grades of steel for the purpose of obtaining quality, uniformity of product, close chemical control, special and complicated analyses. Many of the special carbon tool steels, the highest quality alloy steels, the aircraft steels, the semi- and full-corrosion-resistant steels, the special heat-resistant steels, the alloy tool steels, and the high-speed steels are made in the basic arc furnaces.

The other electric furnace, which is used fairly widely at the present time, is known as the high-frequency coreless induction furnace. It is of recent origin as it was first put out in 1917 and was used entirely as a laboratory tool and for melting precious and semiprecious metals until 1922. In the past 10 years its expansion has been rapid and the furnace has been increased in capacity until the larger sizes in use at the present time will hold 8,000 lb.

The high-frequency induction furnace is being used both in the making of ingots and in the steel foundry. In ingot practice, it is best adapted to the manufacture of stainless (18 per cent Cr, 8 per cent Ni) steel, high-speed steel, and other special steels. It is not a refining process as it produces steel from pure scrap and ferroalloys only at the present time, and is really an adaptation of electricity to the crucible process. Owing to its flexibility, it is used more in the steel foundry than in ingot production. Hence the description of the furnace and its operation will be deferred to Chap. XVII. Owing to its several advantages, however, this furnace is being used more and more in tonnage practice and seems destined for a very important place in the production of high-quality ingots of special steels in the future.

The production of steel by means of either the arc or the induction furnace has several important advantages over the other steelmaking processes:

1. Positive temperature control, as well as any desired temperature can be obtained. The temperature can be easily controlled by controlling the electrical input and, in addition, much higher temperatures can be attained than can be reached with the open-hearth furnace.

2. Freedom from contamination of the bath by the source of heat. The absorption of sulfur from the furnace gases in the open-hearth is avoided in the electric furnace.

3. Either oxidizing, reducing, or neutral conditions can be produced at will in the furnace. This is of considerable advantage as it permits complete deoxidation in the furnace as well as the addition of any alloying elements in the furnace.

4. Controlled and significant elimination of sulfur, nonmetallic impurities, and occluded gases can be effected. The elimination of sulfur can be done only in basic practice while the electric process in general matches the crucible process in the elimination of solid nonmetallics and gases.

These advantages have all played their parts in the rapid development of the electric processes. The future of electric melting and refining seems very bright at present.

The Heroult Electric Arc Furnace.—The various types of arc furnaces designed and built differ mainly in the way the electrodes are introduced into the furnace and the manner in which the arc

is struck. The popularity of the Heroult furnace, described in this section, is due to the following factors:

1. The manner in which the arc is maintained results in a furnace of maximum efficiency.
2. The construction has proved to be simpler than with other methods of introducing the electrodes.
3. The furnace is more easily adaptable to wide variations in practice.

The manner in which the arc is struck in the Heroult furnace can be seen in Fig. 1-V. All three of the electrodes (only two are shown in the section) enter the furnace vertically through

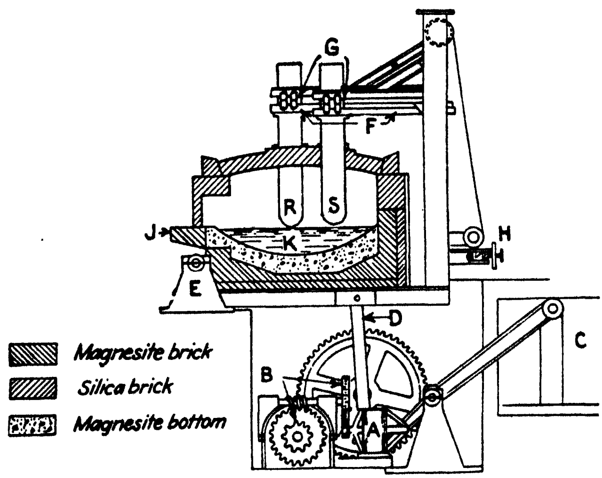


FIG. 1-V.—Heroult-type electric furnace. (*From "National Metals Handbook."*)

the roof and project to within about an inch of the slag. Three-phase alternating current is used and the arc, which produces most of the heat, is struck between each of the electrodes and the bath in succession. The electrodes are set too far apart for the arc to jump between the electrodes themselves. In the conduction of an electric arc, the current is conducted through space by means of vaporized particles from the electrodes, in this case principally carbon particles from the graphite or amorphous carbon electrodes. If we consider the current to be entering at electrode *R* (Fig. 1-V), it jumps the gap at the foot of *R* and passes into the slag, forming an arc in the process. The slag has a high electrical resistance (generating more heat),

and the current passes into the metal bath below, which is a good electrical conductor. The current is then conducted to the region under the foot of electrode *S* by the metal bath, passes through the slag, and arcs to the electrode. Practically all the heat produced by the current is formed by the arcs between the electrode and the slag, which protects the metal from the intense

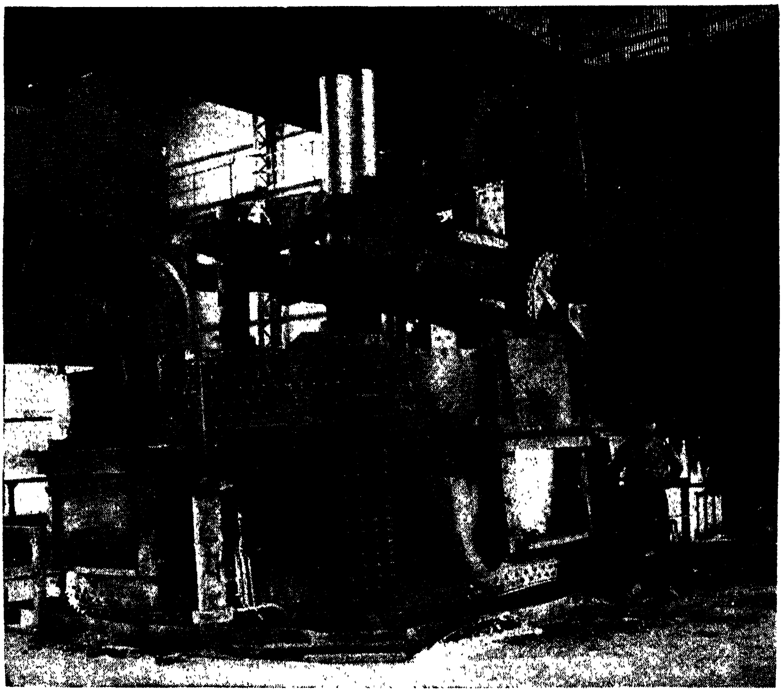


FIG. 2-V.—An electric arc furnace. (*Courtesy of the Carnegie-Illinois Steel Corp.*)

heat of the arc and the carbon vapor produced by it. The heat enters the metal by conduction through the slag and by radiation from the walls and roof of the furnace to the metal. The heat is distributed through the metal by means of conduction, convection currents, and a slight stirring effect in the neighborhood of the electrodes caused by the current. The temperature at which the electric arc operates is extremely high. Some indication of the actual temperature can be obtained from the knowledge that carbon vaporizes at about 3500°C., and the arc is conducted by means of the carbon vapor. Of course, neither the metal nor

any other part of the furnace ever approaches that temperature except for the air space at the foot of the electrodes.

Commercial units are built in several different sizes, the usual capacities being 1, 3, 6, 15, 25, 40, and 100 tons. The transformer capacities required for them vary from 1,000 to 25,000 kva. All but the 100-ton furnace have three electrodes, the hearth area of the 100-ton furnace being so large as to require two sets of three electrodes. Figure 1-V is a drawing of a 6-ton furnace and accessories, while a picture of a furnace is shown in Fig. 2-V.

The furnace itself is circular in cross section and constructed of a steel shell lined with high-quality refractory. The roof is arched slightly and is removable for mechanical charging from a crane in the larger furnace sizes; the smaller ones have doors on the sides for hand charging. All sizes have doors in the side of the shell through which the heat can be worked. The furnace rests on a platform which can be tilted for pouring the heat and from this platform, at the back of the furnace, rises the support for the electrodes. The tilting mechanism is located underneath the furnace in the manner shown. The mechanism consists of a motor *A* which raises the furnace by means of a connecting rod *D* operated through the series of gears *B*. The weight of the furnace is balanced by the counterweight *C*. The furnace is tilted by this mechanism about the stationary axis *E*, just under the spout *J*.

The electrodes, three in number and arranged at the vertices of a triangle, are from about 6 to 24 in. in diameter and are made of either graphite or amorphous carbon. They are usually furnished in lengths of 6 ft. each and threaded at each end so that one length may be screwed into the end of another. In this way butt ends of electrodes can be utilized because, as an electrode is used up, another length can be screwed into it and continuous feeding maintained. The electrodes are independently supported in electrode holders on horizontal supports which can be moved vertically on guides in the vertical support. Each electrode is independently controlled by a winch motor which automatically keeps the bottom of the electrode the correct distance above the slag. As the height of the electrodes above the bath controls the heat input to the furnace, a setting of this distance fixes the heat input (with constant voltage) and the

winch mechanism automatically keeps the electrodes at the required distance, lowering them as they are used up. Water-cooled collars surround the electrodes where they enter the furnace. The current is brought to the furnace by means of heavy cables, while the bus bars *F* and electrode holders *G* convey it to the electrodes themselves.

The hearth of the furnace is made up much as in the open-hearth process. Figure 1-V is a drawing of a basic furnace. The bottom is necessarily of magnesite brick and layers of sintered magnesite. In the acid furnace, the bottom is made of sintered layers of silica sand, backed by fire-clay brick. In either case a slag wash is used as in open-hearth practice. The bottom is sintered in by the heat of electric arcs formed between the furnace electrodes and other electrodes placed across the hearth of the furnace. The side walls above the slag line and roof of both types of furnaces are lined with the best grade of silica refractory obtainable, as these parts are subjected to severe service. The refractory arches, jams, and door brick, particularly, have a short life, although water cooling will lengthen materially the life of these parts.

The furnace itself is usually elevated somewhat above the charging floor and so placed that its contents can be poured into a steel ladle placed below the pouring spout. The control panel and transformers are usually located in a separate room adjacent to the furnace to protect the electrical instruments from dirt. The voltage input to the furnace can be controlled by switches on the panel so that several different steps in voltage can be obtained. The tilting mechanism and electrode control apparatus are often located in separate rooms to protect them from dust and from the danger of heats burning through the bottom and running into the pit. Details of design and installation differ somewhat in different furnaces, but the above description is typical of most commercial installations.

The Acid Electric Process.—In localities where electric power is comparatively cheap, the acid electric process is able to compete with the acid open-hearth in the production of the same types of steels—high-quality forgings, ordnance and alloy steels, etc. The furnace charge is usually nearly all if not all scrap and practically the same purifying procedure is used as is common in connection with the acid open-hearth. In the electric process,

however, the bath can be more thoroughly deoxidized since the oxidizing effect of the furnace gases on the slag is eliminated, allowing the bath more nearly to approach equilibrium with a minimum amount of FeO in it.

The time necessary to refine pig iron in the electric furnace is so great that it is prohibitive under nearly all conditions, and the process is used mainly to melt and refine carefully selected scrap low in phosphorus and sulfur, as the process will remove neither. If alloy steels are being made, the required amount of ferroalloys is added near the end of the deoxidation period. The process has all the advantages of an acid process over a basic one, as well as its disadvantages. In addition, it has the general advantages mentioned above of electric over fuel-fired processes, such as quicker melting, greater ease of refining and temperature control, more complete deoxidation, and cleaner steel.

The acid electric process is used in the production of ingots for the purposes mentioned above but, since a far greater tonnage goes into the production of steel castings, the details of the operation of the furnace will be deferred to Chap. XVII.

The Basic Electric Process.—By far the majority of ingot production by electrical methods is produced by the basic electric process. One reason for this state of affairs is that a basic slag can be built up in the process which, in conjunction with neutral or slightly reducing conditions produced, has an affinity for sulfur. With good practice, the bath can be made very free from sulfur. The controlled and nearly complete removal of sulfur cannot be obtained by any other process and pure, clean steels can be made which are superior to those made in the basic open-hearth furnace and perhaps equal in quality to any steels that are made.

The basic electric furnace is used in two principal ways: (1) as an adjunct to the basic open-hearth furnace, in which steel is first processed in the basic open-hearth and then "super-refined" or completely deoxidized in the basic electric furnace, and (2) as an independent process in which cold charges (principally scrap) are melted and refined entirely in the basic electric furnace. The first method is used in plants producing large tonnages of electric steel and will be discussed in Chap. VI. The independent use of the furnace, called the "cold melt process," is the subject of the following discussion.

Normal Alloy Steel Practice.—The furnace charge consists mainly of selected steel scrap of such a composition that the carbon content, at least, will be lower in the bath when melted than is required in the finished steel. If possible, the amounts of the other impurities in the charge are kept below the amounts required in the finished steel because the time necessary to eliminate them increases the cost of the process considerably at the usual cost of electric power. For this reason, pig iron is rarely a part of the initial charge. It is not always possible, however, to obtain scrap of the desired composition and some reduction in impurities such as phosphorus, carbon, manganese, and silicon is necessary. The reduction of manganese, carbon, and silicon below the final values required allows for the final necessary adjustment of the composition with ferroalloys and carbon additions.

The physical condition of the charge is of as great importance as its chemical composition, since the speed of melting and hence the cost depend upon it. In addition, the ability of the charge to conduct heat and electrical current and the distribution of the charge in the furnace all have a bearing on the economy of the melting stage of the process. Care is taken, therefore, to maintain a proper balance between the amount of heavy and light (small-sized) scrap charged and in distributing these so that the charge will melt with a minimum of delay.

The melting down of the charge is usually carried out as quickly as possible to decrease the cost of power and the losses of metal due to oxidation. A high initial voltage of about 200 to 250 volts is required for this. Later on in the process, however, a much lower voltage of from 85 to 100 volts is used. This is the reason why most furnaces are now equipped with multi-voltage transformers. For the first 15 or 20 min. of melting, the electrodes usually "search," *i.e.*, they are raised and lowered by the automatic regulator as they melt through the scrap charge, causing a widely fluctuating current in the furnace. The reason for this is that the scrap falls away from the electrodes very rapidly in melting, leaving too much space for the regulator to take up quickly, and the arc fails. The regulator then moves the electrode down until it makes contact with the charge and then raises it to the correct arcing distance again. This process is repeated until a molten pool of metal is formed under the

electrodes. This "searching" of the electrodes results in quite a loss of time and power if the scrap is not correctly proportioned and charged in order to give good conductivity for the current. It is the reason why some operators like to charge a small amount of liquid open-hearth metal to form the molten pool at the beginning and work the scrap into it.

As soon as the molten pool of metal is formed under the electrodes, a steady arc condition sets in, the temperature of the furnace rises rapidly, and the melter starts pushing the unmelted scrap toward the center of the furnace. As soon as the charge is entirely molten, the voltage is lowered and the first slag additions are made. The initial slag is made up principally of burnt lime, with small additions of fluor spar and sand to give the required fluidity. This initial slag is basic and oxidizing, the latter being due to the FeO it dissolves from the scrap oxidation.

The refining stage of the process is now begun and the extent of refining, as well as the matter in which it is carried on, depends upon what impurities must be removed and to what extent they must be eliminated. This stage of the process is important since, owing to the excellent control of the furnace atmosphere, it is one of the main reasons for the superiority of the electric over the open-hearth process. If the removal of oxidizable elements is required, this is done by adding FeO to the slag in the form of ore or scale and oxidizing the impurities out as in basic open-hearth practice. Since the FeO in the slag is not oxidized by the furnace atmosphere, the extent of oxidation can be closely controlled by the FeO addition. If phosphorus is to be removed, the temperature of the bath is kept low as its removal is favored by low temperatures and high basicity of the slag. As soon as the required amount of phosphorus is removed, the temperature of the bath is raised as high temperatures favor the removal of carbon. The refining period also eliminates silicon and manganese and, as soon as all the impurities except sulfur have been lowered to values considerably below the amounts required in the finished steel, the furnace is tilted slightly and the black or oxidizing slag is raked off as completely as possible.

The reactions by which the impurities in the bath are oxidized are the same as those encountered in the basic open-hearth

process and will not be repeated here. The control of their removal is much better in the electric process because the only oxidizing agent is FeO, and its amount is under the control of the melter. The phosphorus removal is carried out quite completely at the lower temperature and hence without burning out much of the carbon and, if it is desired to burn out carbon, the temperature can then be raised to effect its rapid removal. The black slag is highly basic and quite oxidizing in nature and contains the oxides of phosphorus, silicon, and manganese, usually combined in some form, in addition to CaO and SiO_2.

If the carbon content of the bath is now lower than the required value, carbon is worked into the bare metal in the form of crushed electrode or anthracite coal. If only a few hundredths of a per cent is needed, low phosphorus pig iron may be added. In case it was necessary to remove only carbon in the refining period, the oxidizing slag is not removed from the furnace but is deoxidized by additions of carbon and the elements contained in it allowed to reenter the metal. If the black slag were removed, a new basic slag, consisting of lime, sand, and fluor spar, with sufficient coke to form calcium carbide, is now built up. This new reducing or deoxidizing slag is usually called a "white slag" because of its color.

The deoxidizing stage of the process is now begun. The metal can be considered as containing dissolved FeO and CO and suspended oxides of manganese, silicon, chromium, etc. The new basic slag picks up oxides from the bath quite rapidly, principally FeO, MnO, and SiO_2. It is necessary to remove these impurities in order to make high-quality steel. The principal deoxidizing agent, calcium carbide (CaC_2), is formed by a reaction between CaO and the carbon added

$$CaO + 3C = CaC_2 + CO$$

and occurs only when the furnace atmosphere is nonoxidizing. The carbide deoxidizes the slag by the reactions

$$3FeO + CaC_2 = 3Fe + CaO + 2CO$$
$$3MnO + CaC_2 = 3Mn + CaO + 2CO$$

and the iron and manganese are returned to the metal, as well as chromium, tungsten, vanadium, etc., if they were present as oxides in the slag. As the foregoing reactions use up the carbide

in the slag, more carbon must be added from time to time to combine with the CaO liberated and keep the slag deoxidizing in nature. This procedure is kept up until the slag shows an excess of calcium carbide. This is tested from time to time by immersing a cold sample of the slag in water. If acetylene gas, which burns and has a peculiar odor, is generated, the slag contains excess CaC_2. The equation for the gas formed is

$$CaC_2 + H_2O = C_2H_2 + CaO$$

The slag is maintained strongly basic and reducing in nature throughout this portion of the process.

The carbide in the slag will not, however, deoxidize the steel, except where they come in contact with each other. The carbide in the slag reacts with the FeO and CO in the metal at the contact surface and, of course, would deoxidize the steel after a very long time by diffusion of the FeO. This action can be hurried considerably by stirring the bath in order to bring the slag in contact with as much of the metal as possible and reduce its FeO content. As the amount of deoxidation that can be accomplished in this manner is limited, final deoxidation is accomplished by metallic additions. During this holding period, however, nearly all the solid and liquid impurities will have time to rise into the slag. Also, the manganese reduced from the slag by the carbide reaction helps immensely in removing the dissolved FeO and CO from the metal by the reaction

$$Mn + FeO = Fe + MnO$$

and the MnO frees itself from the bath.

During the deoxidation period, the sulfur is being removed from the metal. Sulfur, in the form of FeS and MnS, reacts and is removed as follows:

$$\begin{aligned} FeS + CaO + C &= Fe + CaS + CO \\ 3FeS + 2CaO + CaC_2 &= 3Fe + 3CaS + 2CO \\ MnS + CaO + C &= Mn + CaS + CO \\ 3MnS + 2CaO + CaC_2 &= 3Mn + 3CaS + 2CO\cdot \end{aligned}$$

The gas formed is held in solution in the highly basic slag. The major part of the desulfurization by means of CaC_2 is not carried out until the slag is nearly completely deoxidized because of the following reactions:

$$CaS + FeO = FeS + CaO$$
$$CaS + MnO = MnS + CaO$$

The almost complete removal of sulfur from the bath by this method is impossible by any other commercial steelmaking process.

When the bath is nearly completely deoxidized, owing to the foregoing reactions, the composition can be adjusted to conform to the values desired in the finished steel. Throughout the refining and deoxidation period, samples are taken to the laboratory for rapid chemical analysis in order to determine the progress of the elimination of impurities and the required amount of alloying elements to be made. Close cooperation between the laboratory and the melting floor is necessary in order to operate the process within narrow limits of chemical composition. The addition of alloying elements to the bath in the form of ferroalloys can be made without danger of excessive loss and they are usually made about a half an hour before tapping. Final deoxidizers are added immediately afterwards, such as ferrosilicon, ferromanganese, or double deoxidizers (calcium silicide, aluminum-silicon alloys, etc.), and the heat is held in the furnace for temperature adjustment and for the products of deoxidation to rise out of the bath. This holding period in the furnace under a deoxidizing slag and under neutral or reducing conditions of furnace atmosphere accounts for the freedom of electric steel from occluded gases and nonmetallic impurities.

When the composition of the bath is at the desired value, the melter takes tests to determine the temperature of the bath and the extent of its deoxidation. The film test for temperature is fairly accurate in the hands of an experienced operator and consists in filling a slag-coated spoon with metal and noting the time necessary for a film to freeze over the surface of the steel. With many alloy steels, this procedure is not sufficiently accurate and the temperature is determined by pouring a spoonful at a certain rate into a small test mold. When the correct tapping temperature is reached, no metal will remain in the spoon and the test piece will not have wrinkled sides. If the bath is free from soluble oxides, the top surface of the test piece will be smooth, free from bumps or eruptions, and slightly depressed in the center. These tests are only relative but tell an experienced melter the progress of the heat.

A log of a normal alloy steel heat is given herewith.

ARC-FURNACE RECORD* OF NORMAL ALLOY HEAT. 15-TON FURNACE
Analysis ordered: C, 0.15/0.20%; Mn, 0.40/0.60%; S, 0.025%; P, 0.025%; Si, 0.15/0.30%; Cr, 0.45/0.75%; Ni, 1.00/1.50%

8:30 A.M.	Previous heat tapped
8:40	Began charging: 36,000 lb. common scrap 256 lb. nickel 120 lb. anthracite
9:10	Finished charging; power on high voltage
10:10	Add lime, 300 lb. intermediate voltage
11:00	Add lime, 300 lb. low voltage
11:15	Add iron ore, 200 lb.; nearly melted
11:25	Add iron ore, 250 lb.; completely melted
11:40	Bath stirred. Carbometer test 0.06%C
11:42	First steel and slag test
11:45	Start slag off
12:00	Finish slag off
12:08 P.M.	Refining slag mix added: 800 lb. lime 150 lb. fluor spar 100 lb. sand 90 lb. coke
12:20	First steel test reported: 0.16% Mn, 0.012% P, 0.77% Ni, 0.04% Cr
12:30	Add coke, 90 lb.
12:45	Bath stirred; slag carbide
12:50	Second steel and slag test
12:55	Add coke, 50 lb.
1:10	Stir bath, temperature test
1:15	Add chromium, 270 lb.: 70.00% Cr, 4.60% C
1:20	Add coke, 40 lb.
1:30	Second steel test reported: 0.08% C, 0.15% Mn, 0.026% S, 1.24% Ni, 0.05% Cr
1:35	Stir bath; temperature test
1:40	Add manganese, 182 lb.: 80.00% Mn, 6.70% C
1:40	Add silicon, 106 lb.: 76.00% Si
1:55	Power off; stir bath; temperature test
2:00	Tapped

Ladle analysis: 0.17% C, 0.57% Mn, 0.013% P, 0.015% S, 0.22% Si, 1.22% Ni, 0.57% Cr.

	Slag analysis, per cent									
	CaO	SiO_2	FeO	Fe_2O_3	Al_2O_3	MgO	MnO	P_2O_5	S	CaC_2
First....	38.59	10.52	18.16	6.44	2.20	8.00	9.28	0.59	0.14	
Second..	60.86	17.30	0.97	Nil	0.72	4.10	0.40	Nil	0.31	2.40
Tapping.	63.74	20.19	0.58	Nil	0.30	8.25	0.10	....	0.32	2.00

* FARNSWORTH and JOHNSON, American Electric Furnace Practice, *J. Iron Steel Inst.*, **138**, No. 11 (1938).

Tapping and Pouring.—All the different types of heats produced in the basic furnace are handled in much the same manner with respect to tapping and pouring. All possible precautions are taken to prevent contamination of the metal. The tapping of the finished heat is carried out with the greatest care since it is highly undesirable to mix the steel and the slag in the ladle. The usual practice is to tilt the furnace at such a rate that the slag level is kept above the taphole, thus holding back the slag until the tap is complete.

The ladles used are of the bottom-pour type, with mechanism on the side for operating the stopper rod. Particular consideration is given to the selection of the refractories in the ladle from the standpoint of softening and spalling at high temperatures. The ladles are thoroughly cleaned and preheated as hot as possible before using. The nozzle size varies, depending upon the type of steel and the size of ingots cast. In pouring, the usual precautions are exercised to pour at a proper rate in order to avoid splash and ensure a good surface. The size of the ingot in most cases is governed by the size of the finished product. For normal alloy steel practice the molds are prepared by applying a tar coating on the inside surface; while for special heats, where it is necessary to avoid carbon pickup, such coatings as aluminum powder, shellac, and alcohol are used instead of tar. Several types of sinkheads or so-called "hot tops" are used. With respect to ingot soundness and yield, little advantage can be claimed for one over the other. The choice of mold design and hot top is governed to a large extent by the results obtained from experience with the various types of steels. After the ingots are poured and sufficient time is allowed for solidification, they are loosened from the molds and sent to the blooming mill or forge shop for further processing.

Suggested Questions for Study and Class Discussion

1. What advantage does the electric furnace have over the other steel-making methods?

2. Why are acid electric furnaces not extensively used?

3. What serious drawback does the electric method possess? Why is pig iron seldom added in the electric furnace process?

4. How is the heat supplied to the bath in the electric process?

5. Why are three electrodes normally used? What type of current is used?

6. What are the typical capacities of electric furnaces?

7. Why are electric furnaces normally tilting in construction?

8. Is a lime boil employed in the electric process? Why?

9. How is the FeO introduced and controlled in the electric process? Why can the FeO be controlled better in the electric than in the open-hearth process?

10. Show the steps involved in making an average heat of electric furnace steel, giving the time required for each step.

11. In what way does the method of deoxidation in the electric process differ from that used in the open-hearth process?

12. Why can sulfur be removed more completely in the electric process than in any other steelmaking method? Give the equations.

13. How is it that a heat can be held in an electric furnace for a much longer period after deoxidation than in an open-hearth furnace? What advantages accrue from this fact?

CHAPTER VI

THE SPECIAL STEELMAKING PROCESSES

The so-called special steelmaking processes fall into two general classes:

1. Those in which a modification of a standard process is used for the purpose of speeding up the operation or utilizing an inferior grade of raw material, or both.
2. Those in which a combination of two or more standard processes is used, with or without modification, for the purpose of producing a large tonnage of steel quickly or making a high-grade product from low-grade raw materials, or both.

These processes will be taken up briefly in approximately the order of their importance, and their classification will be evident from the description. The special processes are used in such a wide variety of ways that only a general idea of the methods used will be given here.

The Duplex Process.—In some large plants, the acid Bessemer and the basic open-hearth are used in succession, resulting in the duplex process. Most of the carbon and all of the silicon and manganese are oxidized in the converter and the product transferred to a basic open-hearth furnace where the phosphorus and the remainder of the carbon are removed. There are two general methods of carrying out this operation. If pig iron is to be charged into the open hearth with the blown metal, the converter charge is usually blown full, *i.e.*, until the carbon is below 0.10 per cent. The blown metal is then charged into the open hearth, the required amount of molten pig added to bring the carbon up to the normal value when melted, and the heat worked as an ordinary pig and scrap heat after melting. In the second case, if no pig is to be charged into the open hearth, the converter metal is blown only until the silicon and manganese are removed and the carbon is in the neighborhood of 1 per cent. The blow is then stopped, the metal transferred to the open hearth, and the heat worked down as usual. The plant is usually equipped with a mixer between the converter and the open-hearth furnace to

make them approximately independent of each other in their operation.

There are several advantages of the process. The open-hearth purification is shortened to about half the time necessary for the usual cold scrap and molten pig process. The absence of silicon in the open-hearth charge (if no pig is used) cuts down the scouring out of the hearth lining due to SiO_2 in the slag. The first advantage also increases the life of the hearth in terms of steel produced. An advantage of the process from the Bessemer standpoint is that a poorer grade of pig can be charged (not of usual Bessemer grade), and the usual quality of open-hearth steel produced from the product. A disadvantage of the process is that it does not utilize return scrap from the mills and hence is usually used only at times of peak production. Under good conditions, a 100-ton open hearth may produce up to 30 or 40 heats per week by the duplex process, compared to 16 to 18 heats by the ordinary methods.

The Superrefining Process.—This is essentially a special duplex process in which purified basic open-hearth metal is transferred to a basic electric furnace, deoxidized, and finished into high-quality electric steel. The open hearth is generally operated about as usual; the ordinary pig and scrap (or all scrap) charge is worked down in the usual way to low phosphorus and silicon. Care is taken to have the residual manganese as high as possible in the open-hearth product. All, or only a portion, of the heat is transferred to a basic electric furnace and the required amount of carbon added to bring this component near the required finishing value. Since no further oxidation is required, the basic carbide slag is immediately charged and deoxidation and desulfurization of the metal and slag are carried out by the carbide and the residual manganese in the metal. The rest of the additions are made in the same manner as in the cold melt basic electric process.

A very evident advantage of the process is that much time is saved in the electric furnace. Consequently, the cost of the process is lowered through saving in power. Furthermore, excellent grades of alloy and tool steels may be made by this process from raw materials cheaper than those with which it is economical to operate the cold melt process. This process is quite widely used in tonnage electric steel production.

The Triplex Process.—This process is carried out in two ways: (1) a combination of the acid Bessemer converter, the basic open-hearth, and the basic electric in succession, or (2) a combination of the acid Bessemer and two basic open hearths in succession. The first modification is only a combination of the duplex and the superrefining process and needs no further comment. The second is used when the blast furnace produces pig iron from ores very high in phosphorus. The high phosphorus pig (about 1 per cent P) is blown in the Bessemer and transferred to a tilting open hearth where the heat is worked down to about 0.07 to 0.10 per cent P. The heat is tapped, separated from the slag, and charged into another open hearth where a new slag is built up, and the rest of the phosphorus and carbon removed. Sometimes, the heat is recharged into the same furnace after the slag is separated on tapping.

This second combination is used very little in the United States because only the Alabama ores are high enough in phosphorus to make the process necessary. It is used to a considerable extent in Europe, where the first high phosphorus slag is crushed and sold for fertilizer. The tap from the first open hearth to remove the slag is necessary because it would not be possible to deoxidize the metal in the presence of such a high phosphorus slag without the reversion of too much phosphorus into the metal. Also, the second slag is not so rich in FeO and hence the heat can be more thoroughly deoxidized, resulting in better quality of product.

The Talbot Process.—This process is an attempt to make the basic open-hearth process continuous in operation and results in a very large tonnage of metal in a very short time. The process uses a 200- to 300-ton basic-lined tilting furnace. This increase in capacity is obtained by using a bath of metal 40 or more inches in depth rather than by increasing the length and width of the hearth very much. The first charge, usually consisting of pig and scrap, is worked down to the desired composition in the usual way, the greater part of the slag poured off, and about one-third of the metal tapped. Ore and limestone are now added to the bath to produce a very basic, oxidizing slag, and enough molten pig iron is poured through the slag to equal the amount of metal tapped. The reaction between the impurities in the pig and the highly oxidizing slag is very rapid, since the pig is poured through

the liquid slag. It is so rapid that the silicon and manganese are eliminated from the pig almost immediately, together with most of the phosphorus, as the furnace temperature is allowed to fall at this point to effect rapid removal of phosphorus. During this period much of the slag runs off and the heat is then worked down to the required carbon and phosphorus values as the temperature of the bath is raised. By the end of from 3 to 6 hr., the bath is again purified and another 80- to 100-ton heat is tapped. The slag is reoxidized, more pig added, and the procedure repeated. The process is thus continuous for about a week. At the end of this time, the hearth is in such bad shape that the furnace must be drained and the lining patched.

The advantages of the process are that about four heats of ordinary size can be obtained every 24 hr.; the process is semicontinuous, and no time is needed for melting scrap; and the yield in steel is high because of the large amount of ore added to oxidize the impurities in the pig. The disadvantages are that the furnace is expensive to install, the repair costs are higher, the process does not use steel scrap (except for the initial charge), and the very large bath causes difficulties in chemical control. The process is, therefore, usually used only at times of peak production.

The Duplex Talbot Process.—This process, as its name indicates, is a combination of the duplex and the Talbot processes. The charge to the Talbot furnace is blown metal from the Bessemer converter, freed of its carbon, silicon, and manganese. As the blown metal is poured through the oxidized slag, the phosphorus is removed almost immediately. Sometimes pig iron is poured in afterward and this addition raises the carbon content of the bath and aids in its deoxidation. A portion of the heat can usually be tapped about an hour after this addition. This method produces steel much more rapidly than the Talbot process.

The Monell Process.—Limestone, ore, and sometimes steel scrap are charged upon a basic hearth and heated until they become pasty. Enough molten pig to fill the furnace is then poured in and, since the temperature is low, the phosphorus will be very rapidly removed during the violent reaction. The slag foams up and pours out of the furnace. The bath is purified very rapidly of its phosphorus, silicon, and manganese, and the carbon is then worked down in the usual manner.

This process appears to greatest advantage on very high phosphorus pig and will refine pig containing 2 per cent phosphorus in about the same length of time that the normal pig and scrap process requires for a charge containing 0.2 per cent phosphorus. Its disadvantages are severe erosion of the hearth from FeO and a large loss of iron in the early slag runoff. This process is used mainly in England and on the continent.

The Campbell Process.—A normal pig and scrap charge is melted in a Campbell tilting basic furnace and held at a low temperature for rapid removal of phosphorus without burning out too much of the carbon. The metal, purified with regard to phosphorus, silicon, and some of its sulfur and manganese, is then tapped into a ladle, separated from its slag, and charged into an acid open-hearth furnace. An acid slag is built up and, since the metal has a composition equal to the usual acid furnace charge after melting, the heat is finished according to usual acid practice. This process allows acid steel to be made from cheaper basic process raw materials but is not used much because of the equipment necessary to operate it.

An Example of Special Practice.—In plants where 200- to 300-ton tilting furnaces and auxiliary equipment are installed for the operation of the Talbot process, it often becomes necessary to make ordinary pig and scrap heats in order to use up the scrap produced in the plant itself. Under these conditions, the method used becomes ordinary basic tilting practice with but one exception. Owing to the large size of the furnace a 200- to 300-ton heat is made at one time and tapped in two or three 100-ton portions, often of different analyses. The following description of a double heat made by this method, as described by the melter in charge of the heat, is given below. The description is not to be considered as general practice but as a typical example of how such a large heat is worked.

At 5:30 P.M. the furnace was rolled back on its big rockers from the tapping position to its normal upright position. The second helper, assisted by the third helper, immediately put a rammer through the taphole on the back of the furnace to be sure that the hole was left clean and free from slag. In the meantime, as the furnace came back to its normal position, the first helper looked over his slag line, for on a tilting type furnace there may be a residue of metal and slag still in the furnace. He then raised

the producer gas valve and allowed the gas, which had been shut off when the furnace was tilted over, to flow through the furnace.

By means of a dolomite machine, already coupled in front of the furnace, the first helper proceeded to shoot a round of dolomite along the slag line, filling in any places cut by the preceding heats. After making two doors, he reversed the direction of his gas in the furnace so that he had good visibility and did not have to shoot through his gas flame. After shooting the other two doors, he motioned for the first drag consisting of five buggies of limestone (50,900 lb.) and two buggies of scrap to be brought in, and two charging machines started to charge the furnace by working in alternate doors.

While this was being charged, the second helper lined the taphole, using ground wet chrome ore placed on a long-handled paddle by the third helper. When the hole was lined to about a 6-in. size, it was filled with burned dolomite from the inside face to the outside of the furnace.

After the first drag had been charged, the three helpers with shovels faced up the hole with dolomite on the inside of the furnace. The first helper, who had summoned the third helpers from the other furnaces, put a hook with a roller on one of the furnace doors and put up a spoon (about 16 in. in diameter) on a long handle, and with the third helpers putting a shovelful on the spoon at a time, proceeded to make (spoon-up) the front slag line with dolomite, throwing the spoonfuls between the doors on either side and over the door breasts. The first helper usually makes up two doors and the second helper spoons up the other two at the same time. Upon the completion of this, the charging proceeds.

The furnace log showed an allowance of 40 min. on bottom, covering the making of the back and front walls as well as the ends of the furnace. The charge consisted of 114,200 lb. of balled wire, 124,900 lb. of bundled tin scrap, 33,800 lb. of skull scrap, 12,900 lb. of miscellaneous scrap, and 45,700 lb. of rounds, or a total of 331,500 lb.

The furnace was charged from 6:10 to 8:05 P.M., but as the scrap was very light and bulky, it was necessary to melt down the part already charged before the balance could be charged. At 10:00 P.M., to help the melt-down, 35,000 lb. of molten iron was dumped in through one of the end doors on the front of the

furnace. The melt-down took from 8:45 P.M. to 10:15 P.M. The balance of the charging operation was completed at 11:35 P.M. The hooks were again put on the doors and a light round of dolomite put on the front wall, this time a little higher up, and, while the furnace was cool (from the scrap just charged), ground wet chrome ore was used to build up the jambs on the sides of the door openings and the front wall above the slag line between the doors. The doors were then banked up with dolomite and the business of melting the heat started in earnest.

The second helper, during the charging operation, cleaned off the skulls from the runner (tapping spout) and by the use of mud again built up the runner and dried it out by means of a wood fire. The charge was found to have melted to a place where more iron was needed. If iron is added before sufficient scrap is melted to make a bath around the piles of scrap, the cold scrap will cause the molten iron to freeze and will slow up the heat. 50,000 lb. of molten iron was added at 1:20 A.M. and 50,000 lb. at 1:33 A.M., one ladleful being poured through each end door. This iron caused a foam to show around the piles of scrap still sticking up out of the now rapidly forming bath. If the iron were not put in at the proper time, this foam would rise up and flow out the doors and over the ends of the furnace. As the foam disappeared, "fisheyes" appeared on the bath, showing that there was plenty of iron in the furnace for the time being. By 3:00 A.M. there was only a "nigger head" (black knob of scrap) sticking up in one door, and a boil had started in two of the other doors. At 4:00 A.M., a heavy boil had begun in all four doors and the lime began to come up.

By 4:30 A.M., the boil having taken out most of the carbon, the first helper ordered another 50,000 lb. ladle of iron and, with the lime coming up, the slag began to get heavy and to have small chunks of lime floating on its surface.

At 5:30 A.M., the first helper, realizing that the action was going somewhat flat, decided that 30,000 lb. more iron would come close to taking the heat out for him. Word had now reached him that a 0.60/0.62 carbon[1] heat was on the schedule for his first tap and a 0.16/0.22 carbon heat for the second heat.

At 7:00 A.M., in order to thin up the now heavy slag, the three helpers shoveled in six to eight shovelfuls of fluor spar per

[1] 0.60/0.62 means that the carbon content should be between 0.60 and 0.62 per cent carbon.

door, and the basic slag was immediately cut by the fluor spar, thinning the slag considerably.

At 7:45 A.M., the first helper pulled out a test and poured it into a small mold, using a long-handled spoon. This test was broken on the anvil by the second and third helpers. The first helper, by reading the appearance of the fracture, decided that the test showed about 0.15 carbon.

After looking over his furnace, the heavy boils having practically ceased and only slight boils here and there being in evidence, the first helper sent out for 12,000 lb. more of molten iron. After this had worked through the bath, another round of fluor spar was shoveled in to thin down the slag.

By clearing away some of the dolomite on the two middle doors, a couple of boxes of slag were run off into the cinder boxes below the charging floor level. This slag was run off by rolling the furnace slightly forward.

He then took out another test and, without breaking it, sent it to the laboratory to be drilled and run for the preliminary analysis. This test was taken out at 8:20 A.M. At 8:50 A.M., word came back that it showed 0.13 manganese, 0.008 phosphorus, and 0.034 sulfur. This information told him that all he had to do was to clean the furnace bottom of all lime and to shape up his heat.

A test was again taken out and fractured to read the carbon, and the temperature tested by pouring out a spoonful of the metal, watching how it ran out, and whether it left any skull in the spoon. With a high carbon heat he knew that he wanted it to be on the hot side to take up the iron that would be added to the ladle in tapping.

The melter was then called to the furnace and another test taken which still showed about 0.14 carbon. In view of this, an additional 10,000 lb. of iron was added to the furnace. The melter then pushed a 1¾- by 1¾-in. billet (called rod in open-hearth language) into the furnace, dipped it quickly through the slag into the molten metal beneath, and worked it back and forth until the steel melted it off. On pulling the stub out onto the floor, he found a sharp cut and decided that the heat was hot enough to go, and at a temperature of approximately 2850°F.

The melter checked the carbon again by breaking another test and, finding that he had 0.15 carbon, he ordered the deoxi-

dizer (ferromanganese) to be thrown into the bath at 9:40 A.M. and sent out for the recarburizer (hot iron with a high carbon percentage) to put into the tapping ladle to bring his carbon up to the 0.60/0.62 required. In this case, he decided that 28,000 lb. was required. This was put into the ladle and the ladle brought underneath the tapping spout of the furnace.

The second helper cleaned out the dolomite from the tapping spout to almost the inside face of the hole, put in an oxygen pipe, and quickly burned it through. As the metal started out, the furnace was tilted and the ladle filled. With the ladle about one-fourth full, ferromanganese was added to bring the manganese content up to the requirements of the 0.95/1.20 specification.

With the ladle about full, the furnace was rolled back, the ladle covered with a coating of slag, and the heat taken away to be teemed into Gathmann hot-top molds.

For the second heat, the second helper rammed a bag of coal and a few wet bags into the hole to hold the slag back so that as the furnace was rolled over for the second heat, the steel would go into the ladle before the slag. To reach the desired carbon content, 200 lb. of pulverized hard coal was thrown into the ladle, for the bath was found to be about 0.11 carbon, and 0.16 to 0.22 was desired. The ferromanganese should add from 2 to 3 lb. of carbon. In this case, aluminum was added to the ladle to quiet down the action caused by the coal and to get the best teeming results.

During the working of the heat, the first helper varied the gas according to the requirements and reversed it about every 15 min. keeping one eye on the roof so as not to burn (string) it. The second helper had to get up the ferromanganese addition, aluminum, etc., in preparation for the tapping. The third helper helped on the other furnaces and cleaned up around his own, as well as helped with the other work around the furnace. The heats finished 0.60 carbon on the first heat and 0.18 carbon on the second heat.

SPECIAL FERROUS PRODUCTS

American ingot iron and electrolytic iron are two special ferrous products that require brief discussion. Both are nearly pure iron and are manufactured for particular purposes.

American Ingot Iron.—This material is a product of the basic open-hearth furnace, by the careful manipulation of which a commercially pure iron is obtained. Only carefully selected raw materials are used in order to keep the impurities at a minimum. The charge is refined by the usual basic practice to the point where the ordinary basic heat would be deoxidized and tapped. In this case, however, further purification is effected by adding very pure ore to oxidize the small amounts of silicon, manganese, and carbon left in the bath. The metal is then carefully degasified and tapped.

One of the manufacturers of this product, the American Rolling Mill Company, guarantees less than 0.16 per cent total impurity. It usually runs much less. A typical analysis is

	Per Cent
Carbon	0.012
Manganese	0.017
Phosphorus	0.005
Sulfur	0.025
Silicon	Trace
Total	0.059

This material is superior to ordinary carbon steel in corrosion resistance and is used in sheet metal and plate work, such as roofing, pipe, and tanks. It is also used in electrical work since its electrical resistance is low owing to its purity. This brand is sold under the trade name of Armco.

Electrolytic Iron.—Although American ingot iron is the purest iron obtainable by any furnace refining method, electrolytic iron, prepared by electrolytic deposition, is of better purity and is the purest form of iron obtainable by any method.

Two processes are used for obtaining it. In one, the Boucher-Bouchayer process, the electric current flows from a cast-iron anode, which furnishes the iron, through an electrolyte composed of $FeCl_2$ to a revolving rod which forms the cathode. The pure iron is deposited on the rod in the form of a tube and can be later stripped from it. Owing to the fact that hydrogen is occluded in the iron during its deposition, the tubes should be annealed both before and after they are stripped in order to allow the hydrogen to escape. Hydrogen embrittles the iron and the first annealing treatment is necessary in order to strip the tube

from the rod without breaking it. The second annealing treatment is done to ensure the removal of the last traces of hydrogen.

In the other process (Perin-Eustis), iron is deposited from a solution obtained by leaching an iron sulfide ore. A graphite anode permits the current to enter the solution. The method seems to show promise principally because it is the only known commercial method of producing iron from a sulfide ore. Valuable metallic by-products can also be recovered.

Suggested Questions for Study and Class Discussion

1. Give the reasons for the existence of the special steelmaking processes?

2. Describe the operation of the Talbot process.

3. What are the advantages of the superrefining method over the cold melt basic electric process?

4. Where is the Monell process used?

5. Discuss the economic advantages of duplexing.

CHAPTER VII

THE STEEL INGOT

Most of the steel produced by the methods described and discussed in the previous chapters of the text is cast into ingot molds of one type or another, regardless of the type of steel made. In 1942, 85,546,176 tons of steel ingots were produced in this country, and, although this amount has been reduced considerably since then, the figure is a good indication of the size of the industry and the importance of good ingot practice.

A considerable tonnage of the steel made by the various steel-making methods is cast into sand molds of such a size and shape that the desired final shape of the steel part is obtained at once without any further mechanical shaping of the piece. The production of this type of steel product, called a steel casting, is the function of the steel foundry and will be considered in a later chapter. We are interested here in the casting of liquid steel into ingot molds (usually made of cast iron), intended for further mechanical shaping or fabrication in order to obtain the desired shape and size of the final steel product.

By far the greater part of the steel made goes into ingots for further fabrication, for two reasons: (1) because the fabricated products are cheaper or easier to make by this method than by casting, and (2) because of the better physical properties obtained from fabricated products. The importance of the production of good sound steel cannot, therefore, be stressed too much, as the safety of lives and property often depends upon it. If an ingot is improperly made, the internal defects are usually difficult to detect and the finished article, in the form of a ship's propeller shaft, for example, may fail in service with disastrous results. Well-made steel may be completely ruined by poor ingot practice. It should also be remembered that poorly made steel cannot be made into good ingots with the best of ingot practice. Well-made steel is, then, essential for the production of good quality ingots, regardless of the class of steel being made.

THE SOLIDIFICATION OF STEEL IN INGOT MOLDS

In order to understand the effects of the mechanical shaping of ingots on their structure and the means of correcting defects in solidified ingots by improving the ingot practice, it is necessary to understand the mechanism by which liquid steel solidifies in an ingot mold.

In the first place, all metals and alloys are entirely crystalline in the solid state. This statement will have to be slightly modified later in the text, but it is sufficiently accurate for our purpose here. Liquid steel, when carefully purified of metallic oxides (MnO, FeO, etc.), can be considered a homogeneous liquid. By homogeneous we mean that, if any portion of the liquid is selected for chemical analysis and examined it will have the same analysis as any other portion that might be chosen. The atoms of the various elements present, then, are scattered evenly throughout the melt at random. As the metal is cooled, this condition persists until the metal begins to solidify, when the conditions are altered radically.

If all of the melt is kept at the same temperature, solidification will begin at certain favorable positions in the body of the melt, called centers of crystallization, or "nuclei." These nuclei may be assumed to be very small particles of suspended oxides, so small as to be invisible. The building up of the crystals around these various centers occurs by the atoms arranging themselves in a definite pattern which repeats itself. Each crystal grows by causing atoms to change from the random arrangement in the liquid and become a part of the atomic pattern of the crystal itself. Since steel does not solidify at one definite temperature but over a range of temperatures, metal rich in iron solidifies first in a skeleton structure extending in three directions, much as in the model shown in Fig. 1-VII. As the body of metal cools, this skeleton is extended in all directions and the open spaces in the structure itself are gradually filled in with metal, slightly less rich in iron, which transforms from the liquid state and becomes a part of the crystal skeleton. The gradual solidification of the body of metal, all at the same temperature, should be thought of as progressing from many nuclei with the formation of many such crystals. These crystals, of course, finally meet when solidification has proceeded far

enough. When all of the liquid metal has transformed to the solid and crystalline state, the steel may be thought of as being made up of a very large number of these interlocking crystals.

When a solidified steel specimen is correctly prepared for observation, these interlocking crystals can be seen. The original skeleton structure can still be observed and the interlocking effect of the various crystals confirmed. The direction along which each crystal grows most is called the principal axis, and

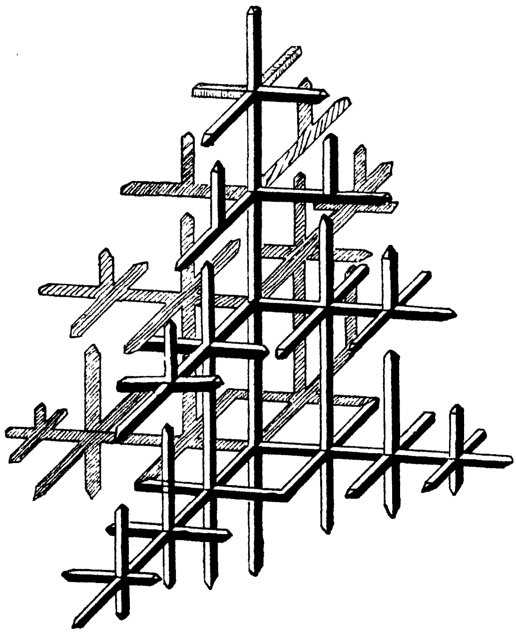


FIG. 1-VII.—Skeleton dendrite of iron. (*After Tschernoff.*)

the branches at right angles to it, secondary axes. The short branches perpendicular to the secondary axes are called tertiary axes. Owing to the likeness of the structure to a tree, the crystals are called "dendrites" and the process of solidification is called dendritic crystallization.

Solidification of Steel in a Big-end-down Ingot Mold.—The foregoing discussion has been based upon a constant temperature of all the metal during the period of solidification. When molten metal is poured into a relatively cold cast-iron ingot mold, this assumption is incorrect and the process of freezing is considerably

different, although the principles underlying it are the same. Since most of the ingots produced in this country are still solidified in big-end-down molds, a description of the freezing of this type of ingot will be given first. The mold will be assumed to be square in cross section with rounded corners, and the metal a killed carbon steel. The mold is shown in vertical section in Fig. 2-VII.

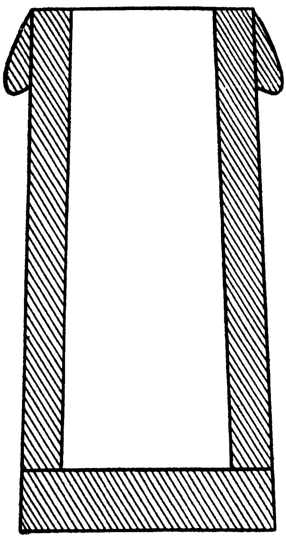


FIG. 2-VII.—Big-end-down mold. (*Courtesy of The Gathmann Engineering Co.*)

As the metal is teemed into the mold, a layer next to the wall solidifies almost instantly, since the heavy mold extracts heat from it very rapidly. The top also freezes over, owing to the cooling effect of the atmosphere, and the molten metal is entirely surrounded by a skin of solidified metal. Crystal growth occurs at right angles to the walls of the mold and continues by growing inward from the walls. Heat is taken from the molten metal less and less rapidly as the mold is heated up until a steady rate of cooling is reached. When this condition is obtained, the heat from the solidified metal and the heat evolved by the solidification of the molten metal is transferred by the mold walls to the outside atmosphere. The rate of cooling is then mainly dependent upon the rate at which heat is taken from the mold by the outside air. The rapid solidification of the skin during the early period chills this metal markedly, but as the normal very slow rate of cooling is reached, the skin is heated up again (but does not melt) by the molten interior of the ingot. From this point on, solidification proceeds slowly from edge to center of the ingot until the metal is entirely solid.

When molten steel transforms from the liquid to the solid and crystalline state, a contraction in volume takes place. This shrinkage affects the cooling of the ingot in two ways. In the first place, as the skin freezes to the walls, it shrinks slowly, and this shrinkage is immediately taken up by the molten pool in the interior of the ingot. Each succeeding layer in freezing

parallel to the mold surface also shrinks and robs molten metal from the center. The pool of molten metal, therefore, gradually sinks down as it feeds the shrinking walls. Since the top of the ingot freezes over very early in the solidification, the sinking of this molten pool leaves a cavity just under the top of the ingot and extending well down into the body of the ingot itself.

The formation of this cavity, commonly called "pipe," is probably the greatest single item of worry and trouble in the manufacture of steel. If the steel manufacturer could eliminate pipe, it would be possible to obtain 90 to 95 per cent of sound steel from all ingots, the only loss resulting from ingot scale and "fishtail" ends in the blooming mill.

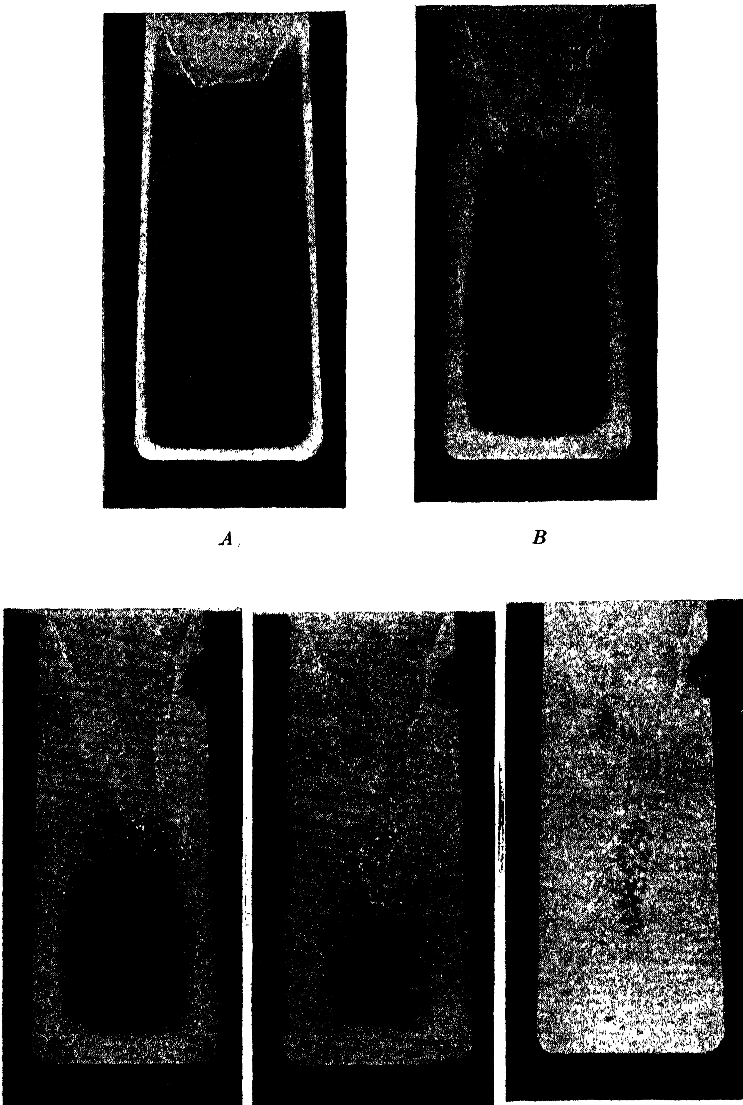
Pipe formation is caused by two factors:

1. Shrinkage (or change in volume) of steel when passing from the liquid to the solid state.

2. Shrinkage of steel when cooling after becoming solidified.

Figure 3-VII shows the formation of this shrinkage cavity very nicely. The figure is a collection of actual photographs taken during the solidification of wax in an aluminum big-end-down mold with a glass front which served as a heat insulator to prevent immediate solidification against the front of the mold. *A* shows the formation of the skin and the beginning of the shrinkage cavity or primary pipe, as it is often called, while *B* shows the enlargement of this cavity caused by continued solidification. The white is the solidified portion, the dark is the liquid portion, and the spotted is the pasty or partly solidified portion of the wax. The balance of the solidification can be followed in *C*, *D*, and *E* of the figure. Since the top of the mold is smaller than the bottom, the upper portion solidifies first and the last portion of the ingot to solidify is in the center of the ingot near the bottom. This is the cause of the extension of the pipe so far down into the ingot, since shrinkage continues as long as solidification is taking place.

The second effect that the shrinkage of steel on solidifying has on the mechanism of solidification is its effect on the surface of the ingot. As the first metal freezes to the walls of the mold, it shrinks and, therefore, draws away from the mold walls, leaving an air gap between the ingot skin and the mold. This shell, then, supports the molten interior of the ingot. There are two serious disadvantages to this state of affairs. The first



A B

C D E

FIG. 3-VII.—The progress of solidification of wax in a big-end-down mold. (*Courtesy of The Gathmann Engineering Co.*)

is that the air gap introduces a high resistance to the transfer of heat from the metal to the mold wall and greatly lessens the effect of the mold walls in chilling the metal. The second disadvantage is that the thin skin of metal is sometimes ruptured by the pressure of the molten metal inside, and produces a roughened surface on the ingot. Both these difficulties can be minimized by proper mold design.

It has been stated that most gases that are soluble in liquid steel are practically insoluble in solid steel. This necessitates an evolution of these gases as the metal crystallizes and introduces another factor in the mechanism of solidification. The chilled portion of an ingot—the rapidly solidified skin—is usually free from blowholes or gas pockets, since the gas evolved can easily rise through the molten interior into the shrinkage cavity. As solidification proceeds, however, some evolved gas begins to be trapped in small quantities in the crystal skeletons as they solidify, causing a porous structure in the interior of the ingot. Most of the gas escapes to the center of the ingot where it is trapped in larger cavities, the size depending upon the amount of gas. This is due to the solidification of the ingot from the top down. The presence of openings below the true shrinkage cavity is called the "secondary pipe" and is due to trapping the dissolved gas as well as to the manner of solidification of the ingot explained above. The entire cavity is often called pipe, no distinction being made between the portions due to the two different causes, *i.e.*, to shrinkage and to the trapping of evolved gas.

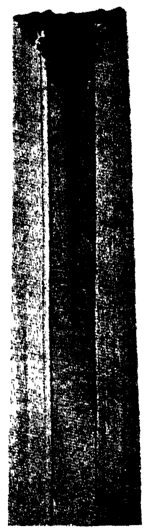


FIG. 4-VII.—Big-end-down ingot of deoxidized steel. (*Courtesy of The Gathmann Engineering Co.*)

If the steel is very well deoxidized, the amount of gas evolved will be very small, practically all the pipe will be due to shrinkage, and the interior of the ingot looks much like Fig. 4-VII. This ingot was prepared by cutting it along the centers of two opposite sides, inserting wedges in the cuts, and breaking the ingot apart. The solidified top over the shrinkage cavity was removed. It can be seen from this that the percentage of absolutely sound metal is comparatively small. If the metal is not so well deoxidized, the interior of the ingot looks like the

example in Fig. 5-VII, in which the secondary pipe can be readily seen as well as the large gas cavities near the top.

Solidification in a Big-end-up Mold.—As has been pointed out above, the big disadvantage of the big-end-down ingot is that the pipe extends so far down into the interior of the ingot. The principal reason for this is that the steel solidifies from the top down as well as from the sides inward. It is obvious that if the metal were made to freeze progressively upward from the bottom and from the outside toward the center, much of the difficulty would be eliminated. The first attempts to produce this effect were made by making the mold walls much heavier at the bottom than at the top and

FIG. 5-VII.—Big-end-down ingot of partially deoxidized steel. (*Courtesy of The Gathmann Engineering Co.*)

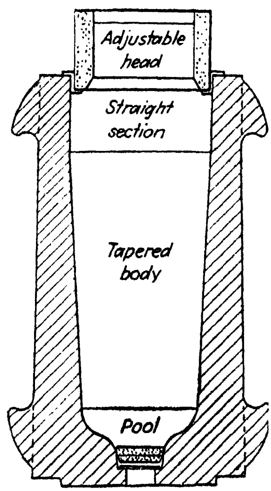


FIG. 6-VII.—Big-end-up ingot mold equipped with adjustable sinkhead. (*Courtesy of The Gathmann Engineering Co.*)

decreasing the taper of the mold itself. This increased the chilling effect of the mold near the bottom and caused more rapid solidi-

fication there, but the trouble was not eliminated until the big-end-up ingot mold was introduced.

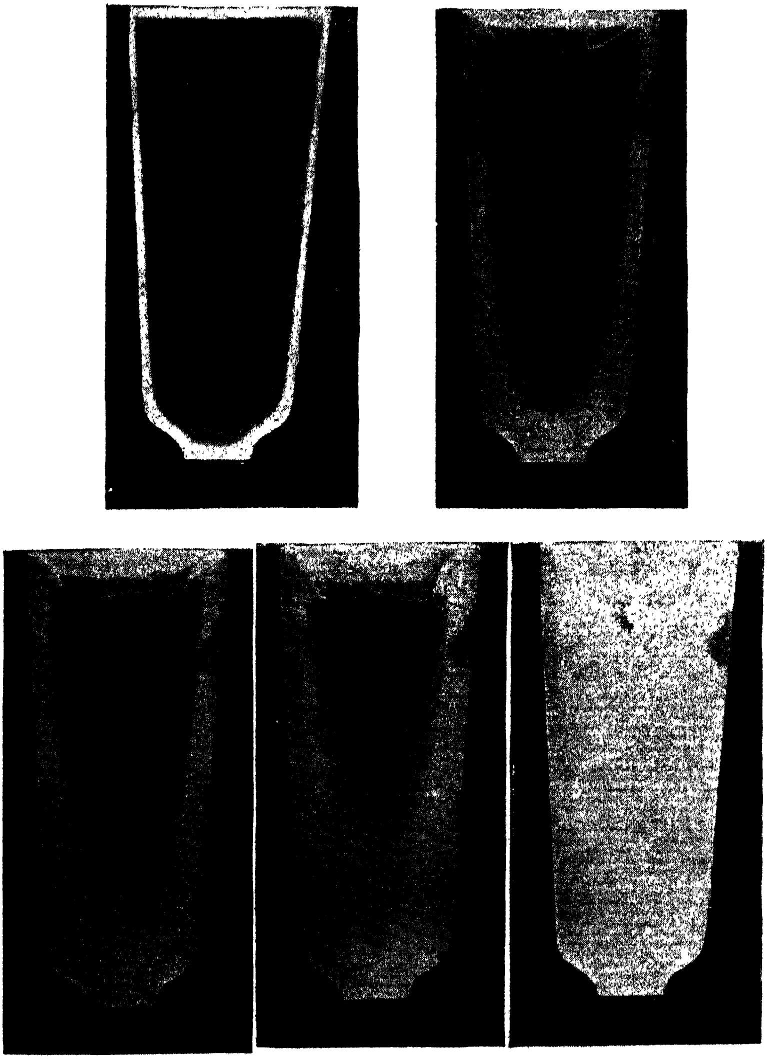


FIG. 7-VII.—The progress of solidification of wax in a big-end-up mold. (*Courtesy of The Gathmann Engineering Co.*)

This type of mold is shown in vertical section in Fig. 6-VII, complete with refractory hot top or sinkhead, as it is sometimes

called. Without the sinkhead, the steel solidifies just as the wax model in Fig. 7-VII. The vast difference between the big-end-up and big-end-down ingots in their manner of solidification can be seen by comparing Figs. 3-VII and 7-VII. The heavier mold walls at the bottom, together with the smaller volume of metal at that point, cause the metal to freeze progressively upward from the bottom. The last metal to solidify is that in the center of the ingot at the bottom of the shrinkage cavity. This confines the shrinkage cavity to a very small section at the top of the ingot, when it can be cut off during fabrication with the minimum of lost metal.

Since a pool of metal extending to the top of the mold is always present and in contact with the solidifying portion of the metal, the gas evolved during solidification can rise to the top of the ingot quite readily. This results in no secondary pipe and comparatively little porosity in killed steel ingots. Furthermore, the taper of the mold helps to support the skin of the ingot in the early stages of solidification. An ingot cast by this method is shown at the right in Fig. 8-VII. The holes and numbers merely mark the places where samples were taken for chemical analysis and are to be disregarded. The figure also shows very clearly the difference between solidification in big-end-up and big-end-down molds.

The Hot Top.—The refractory hot top, when used with the big-end-up mold, as shown in Fig. 6-VII, betters the quality of the ordinary big-end-up ingot. The hot top can be used with the big-end-down ingot mold but this combination is not employed very much as it does not eliminate secondary pipe.

The refractory collar is placed on the mold, as shown in Fig. 6-VII, and a metaltight seal made between it and the mold with clay. The hot top may either be a brick-lined steel shell or made entirely of molded refractory material. If the steel shell type is used, it is carefully removed after the ingot has solidified but, if the all-refractory type is used, it is merely broken off and thrown away. The ingot is stripped by grasping the projecting portion of the ingot with heavy crane tongs and lifting the ingot out of the mold.

The purpose of the hot top is to offer enough resistance to the transfer of heat from the molten metal so that the metal contained in the sinkhead itself will be the last to solidify. As

FIG. 8-VII.—Big-end-down and big-end-up ingots produced from the same heat of fully deoxidized rail steel. (*Courtesy of The Gathmann Engineering Co.*)

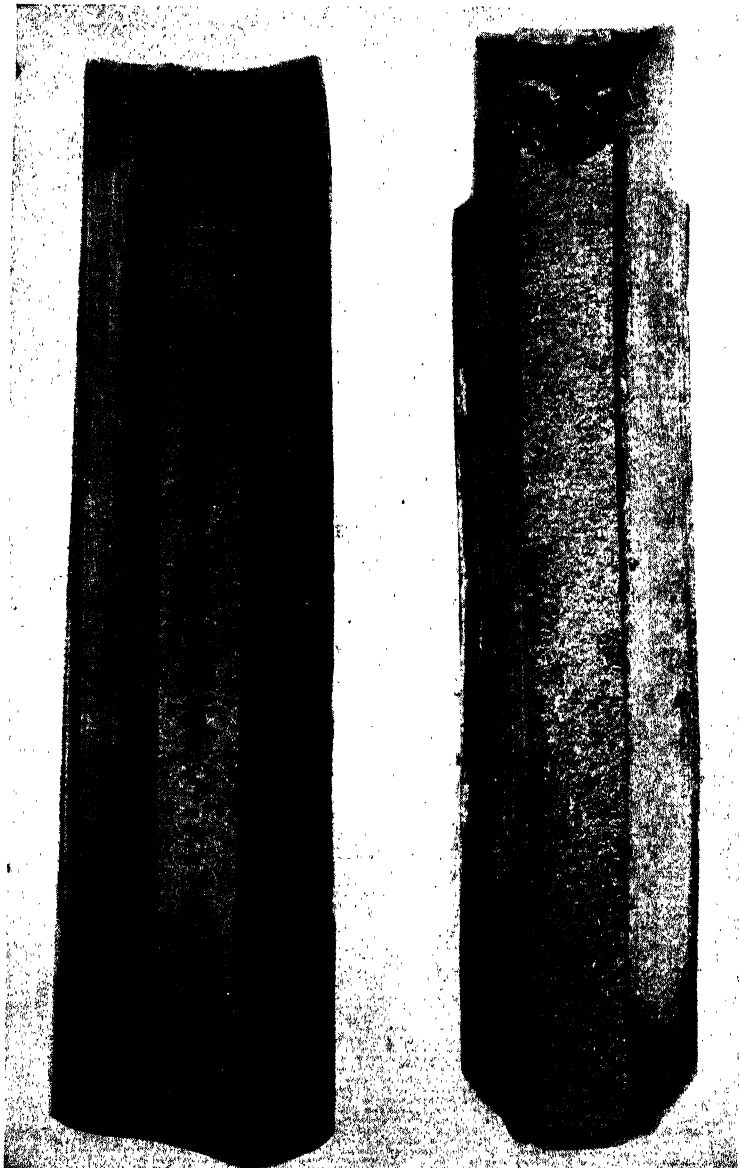


FIG. 9-VII.—Big-end-down and big-end-up ingots cast from the same heat of fully deoxidized steel. Both molds were equipped with hot tops. (*Courtesy of The Gathmann Engineering Co.*)

soon as the mold is filled with molten metal, some refractory substance is thrown on top of the metal to protect it from heat loss in that direction. The metal solidifies much as in the ordinary big-end-up mold, except that, since the metal in the sinkhead is the last to solidify, the pipe is contained in it as shown at the right in Fig. 9-VII. The split ingot at the left in the figure is from the same fully deoxidized heat as the ingot at the right but was cast in a big-end-down mold equipped with a hot top and shows internal porosity very clearly. The hot top is obviously not worth its cost when used on a big-end-down mold.

The action of the hot top is much more positive than the ordinary big-end-up mold without a hot top. In addition, it offers the further advantage of having the pipe contained in a small mass of metal rather than in the largest cross section of the ingot. When the bloom is sheared in the mill, the result is that the entire ingot can be retained for fabrication, only the small sinkhead being cropped. A very small amount is usually sheared from the bottom of the ingot, however.

Use of the Molds.—In spite of the above-mentioned advantages of the big-end-up hot-top mold practice, practically all rimming and semideoxidized steel, as well as some killed carbon steel, is still cast in big-end-down ingot molds. The advantages of big-end-up practice are obtained only at increased cost and steelmakers do not yet consider the advantages to outweigh the increase in cost for these classes of steels, especially since they can still meet specifications with the use of the cheaper big-end-down practice. On the other hand, quality steel for all purposes and all alloy steels are cast in big-end-up hot-top molds, as quality is desired and the higher price is paid to acquire it. Furthermore, this method is necessary in order to meet the specifications for high-quality products. Since the specifications are becoming more rigid year by year for all types of steel products, the trend seems to be definitely toward big-end-up practice.

CHARACTERISTIC INGOT TYPES

The characteristics of different types of ingots made of the three classes of steel can now be discussed and compared.

Killed Steel.—The manner of solidification of killed steels in both big-end-up and big-end-down ingots has been rather fully covered, but Fig. 10-VII shows a comparison on the basis of

longitudinal sections through the ingots. The black portions of the drawings represent cavities and the line and arrows represent the amount of metal retained after cropping. 1-*A* shows the steel cast in a big-end-up hot-top mold and 2-*A* the same steel in a big-end-down hot-top mold. The reason why the hot top is not used on a big-end-down mold can be seen from this comparison, since the hot top does not eliminate secondary piping, although the primary pipe is contained in the refractory portion of the mold. 1-*B* and 2-*B* show the same steel cast into the two types of molds without hot tops and the result of the differences in

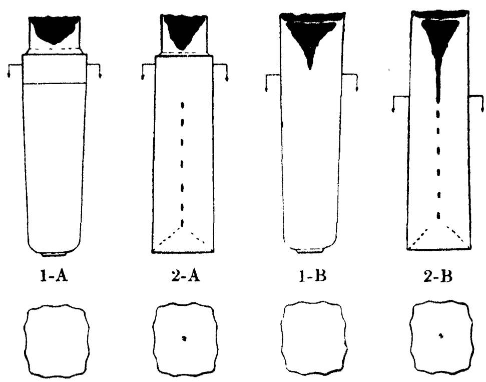


FIG. 10-VII.—Sketches of killed steel ingots. (*Courtesy of The Gathmann Engineering Co.*)

manner of solidification can be readily seen. The pouring and mold temperatures are assumed to be the same in all cases.

High-quality killed carbon steel is now generally cast in big-end-up molds, and alloy steels are almost exclusively cast in this way. The amount of killed carbon steel produced in this country is still small, however, but is increasing as the specifications for soundness became more rigid.

Semideoxidized Steel.—Figure 11-VII shows sketches of the internal structure of several ingots of this class of steel. It should be remembered that this class of steel is made by incomplete deoxidation of the metal and, therefore, the ingots contain blowholes which decrease or entirely eliminate the primary pipe, depending on the amount of blowholes and the manner of solidification. 1-*C* shows the metal cast in a big-end-up mold. The blowholes are concentrated in the upper portion of the ingot,

where the majority of them may be cropped off. The hot top is not worth its cost in promoting soundness in this type of steel. 2-*C* shows the same steel cast into a big-end-down mold. Blowholes extend down the sides of the ingot all around and just under the surface on the bottom. Secondary piping extends almost to the bottom of the ingot. When correct pouring and mold temperatures are used, the blowholes are rather deep-seated, *i.e.*, they are rather deep under the surface. In case the heat is teemed too hot, as in 3-*C*, or too cold, as in 4-*C*, the blowholes extend farther

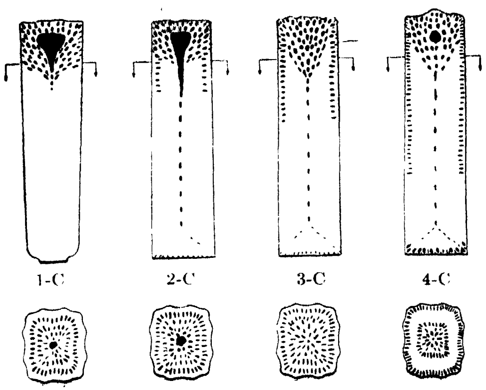


FIG. 11-VII.—Sketches of semideoxidized steel ingots. (*Courtesy of The Gathmann Engineering Co.*)

down the sides of the ingot and are closer to the surface and, therefore, more dangerous. In either case, the metal rises in the mold owing to the space taken up by the blowholes. If the mold is capped to prevent the metal from rising, the blowholes occur under the skin of the entire ingot and usually quite close to the skin. Secondary piping is also increased by capping. An actual photograph of a longitudinal section of a semideoxidized ingot is shown in Fig. 12-VII. This class of steel is very common. It is principally made in medium and high carbon grades (0.25 per cent carbon and over).

Rimmed Steel.—Rimmed steels are those which have received little or no deoxidation so that, when teemed into the ingot molds, there is considerable boiling or rimming action. The rimming action is brought about by a change in solubility of the liquid metal for gas and iron oxide, with the FeO, which has been thrown out of solution as the rimmed ingot freezes in from the mold walls,

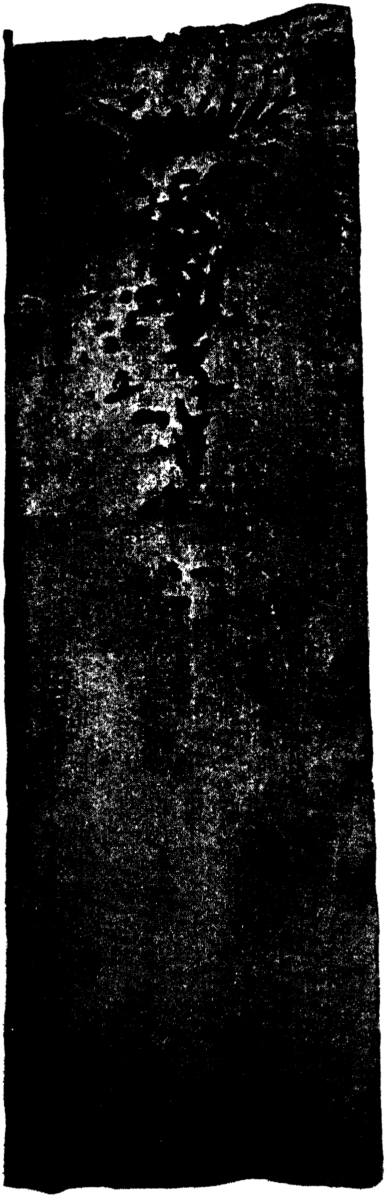


FIG. 12-VII.—Longitudinal section of an ingot of semideoxidized steel. (*Courtesy of The Gathmann Engineering Co.*)

reacting with the carbon in the liquid steel to form carbon monoxide gas. This reaction is as follows:

$$FeO + C = Fe + CO$$

The metal, therefore, must contain a certain amount of FeO and must start to freeze before the rimming action starts. The action, then, is due to the escape of carbon monoxide and other gases from the steel when it is freezing in the mold.

In the freezing action the gas bubbles produced will build up on the inside surface of the freezing ingot until they become large enough to break loose and rise to the top. The important factor, then, is that the gas bubbles must form and rise fast enough or the steel will freeze with the gas trapped very close to the outer surface of the ingot. Two factors can be noted regarding the rising gas: (1) The volume of gas given off increases as it travels upward from the base of the ingot. (2) The rate of travel of the gas increases as it travels upward from the base of the ingot. These two factors account for the fact that a rimming ingot is thicker skinned in the top portions.

The rimming action of a rimmed heat will rim or boil

for 5 to 20 min. depending upon the analysis, quality of the steel, and size of the mold, or until the top has frozen over either naturally or as a result of artificial means such as "capping." During this period some elongated blowholes are formed near the surface of the bottom portion of the ingot because the gases are never released fast enough so that they all escape before the steel freezes. These blowholes are known as "primary blowholes." Their formation cannot be prevented but they can be controlled as far as their location is concerned. The primary prerequisites of the quality of rimmed steels for most purposes are as follows: (1) The surface layer of "skin" between the mold wall and the outside edge of the primary blowholes must be free from any nonmetallics and small blowholes. (2) The primary blowholes must be as far below the surface as possible; in other words, the ingot should be "thick-skinned."

When the rimming action ceases, there is formed a ring of small circular blowholes all around and running from top to bottom of the ingot. These blowholes are known as "secondary blowholes" and are just slightly deeper in the ingot than the inside edge of the primary blowholes. The portion of the ingot from the surface to the secondary blowholes is known as the "rim zone" or "rim."

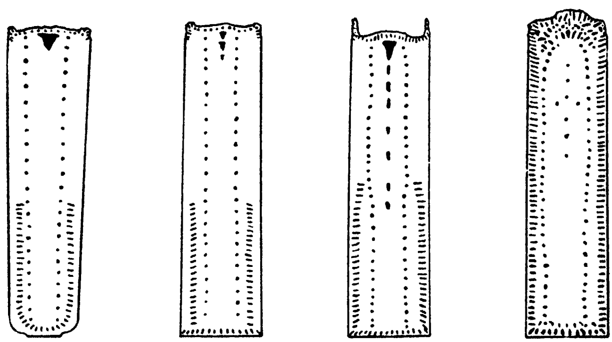
The zone that lies within the rim zone is known as the "core zone" or "core." This portion represents the part of the ingot that has solidified after the rimming action has ceased. In good rimmed steel there is a very abrupt line of demarcation between the rim and the core zones. This demarcation can be clearly seen on macroetch tests of blooms and billets and is found to persist even down to the thinnest sheets. On good rimming steel the primary and secondary blowholes are free of slag and nonmetallic films and will weld together when the ingot is rolled, so that the rim zone on an etch test will be sound and silvery in appearance.

Some of the factors that affect the rimming action of rimmed steel are

1. Chemical analysis. When the analysis runs over 0.25 C and 0.70 Mn, it is practically impossible to obtain a rimming action. This is probably due to the higher carbon and manganese preventing the formation of iron oxide by reducing it as it is formed. High sulfur content (0.10 to 0.15) also tends to reduce the rimming action.

2. Deoxidizing additions. The use of deoxidizers, such as aluminum and silicon, over the optimum, reduces the rimming action because of the reduction of ferrous oxide by the deoxidizers. Frequently, however, on very low carbon heats, a little deoxidizer such as aluminum is used in either the ladle or the mold to prevent violent rimming action.

3. Iron oxide in the slag. High FeO in the slag is desirable since this brings about higher concentration of dissolved oxides in the bath. The result is better rimming action and thicker skinned ingots.



A B C D

FIG. 13-VII.—Interior physical condition of big-end-up and big-end-down rimming-steel ingots. (*Courtesy of The Gathmann Engineering Co.*)

4. Pouring temperature. Higher pouring temperatures are found to give thinner skinned ingots as a general rule.

Figure 13-VII shows the characteristics of rimming steel ingots made in big-end-up and big-end-down ingot molds. In comparing ingot *A* (big-end-up) with ingot *B* (big-end-down) the major difference is that in *A* the blowholes are fewer and deeper seated than in *B*. The difference between the two ingots is due entirely to the mold contour, as both ingots were poured under identical conditions from the same heat.

Ingot *C* is not a true rimming ingot and yet it is not a semideoxidized ingot. In this case the metal rose in the mold and then settled, probably because of the use of excessive aluminum and the fact that the temperature was excessive. An ingot structure of this type is highly undesirable in that it has the shrinkage cavity and intermittent secondary pipe of a semideoxidized steel ingot and its surface in the lower half of the ingot is pitted with

blowholes, which may or may not be deep-seated, as is the surface of a rimmed steel ingot.

Ingot *D* shows the ingot condition resulting from overoxidation of the metal and too low a casting temperature. No deoxidizer was used. This is an extremely undesirable condition both as to its interior and surface conditions.

Figure 14-VII is an actual photograph of a longitudinal section of an open or rimming steel ingot, in the production of which good practice was used. The blowholes are deep-seated and the skin is sound.

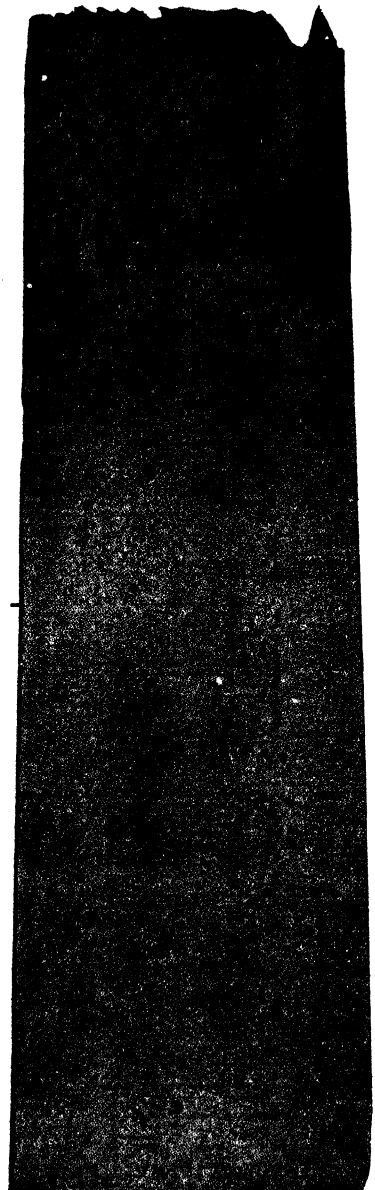


FIG. 14-VII.—Longitudinal section of an open steel ingot. (*Courtesy of The Gathmann Engineering Co.*)

INGOT DEFECTS

Having covered the solidification of steel in various types of ingot molds, a discussion of the defects commonly encountered in steel ingots can be taken up. Some of the defects are inherent in any type of casting and mold practice and can be minimized and controlled only by proper control of the various factors affecting them. Others can be entirely eliminated by correcting errors in the existing practice.

It has only been within the last twenty years that extensive investigations have been undertaken in an attempt to control or eliminate the various defects. Previously, the steelmaker thought that they were inherent in steel, accepted them, and

struggled along as best he could. At the present time, however, sufficient evidence is at hand to show that most of the ingot defects can be controlled and minimized, or even eliminated, by proper manipulation of the heat itself, proper pouring procedure, and proper mold design.

Pipe.—The central cavity in the ingot is called the "pipe." It has been shown above that it is due to two causes. First, the

FIG. 15-VII.—Pipe $1\frac{1}{2}$-in. round resulting from insufficient cropping of the ingot.

shrinkage of steel on solidifying causes a gradual lowering of the molten pool of metal, originally at the top of the ingot, and leaves a cavity above it. The second cause of pipe is the evolution of gas from some types of steel when they solidify. Some of the gas escapes to the molten pool in the center of the ingot. Since, in the big-end-down mold, the metal solidifies from the top down, this gas is trapped at the top of the molten pool of metal. If considerable gas is evolved, an ingot results that contains a shrinkage cavity and numerous smaller cavities (not connected) extending below it. Part of these lower cavities are due to shrinkage and the rest to trapped gases.

The greater portion of the pipe is a source of weakness in the steel and must be removed before finished articles can be made from it. If the surfaces of cavities are not oxidized, *i.e.*, if they are not covered by a film of iron oxide or nonmetallics, the fabricating operation will generally close them and weld them together satisfactorily. If the surfaces of the cavities are oxidized, they cannot be welded together by the pressure of the rolling or forging operation and leave an internal seam in the finished article which is a serious source of weakness. As the ingot is elongated during the fabricating operation, this seam is also elongated at the center of the piece and may be present in a large proportion of the articles made from the ingot (Fig. 15-VII).

The greater portion of the pipe in a steel ingot is oxidized and hence must be removed early in the fabricating process. In addition, pipes are liable to cause breakage of the ingot during rolling and serious accidents may result. The pipe is removed by shearing off the end containing the pipe after the ingot has been sufficiently reduced in cross section to make the shearing operation easy. The cropped portion is returned to the melting furnace.

The cavity due to shrinkage of the metal on solidification cannot be eliminated by any known commercial means, but secondary piping can be practically eliminated by complete deoxidation and degasification of the steel before teeming and by the use of the proper molding practice. The entire pipe can be confined to a relative small portion of the ingot or can be made to form in the sinkhead by the use of the big-end-up ingot mold with a hot top. This is probably the best method of confining the pipe to a known portion of the ingot where it can be removed with a minimum loss of metal.

Blowholes.—Blowholes are small cavities resulting from the trapping of evolved gases in the metal during solidification. The gases dissolved in liquid steel are nitrogen, carbon monoxide, carbon dioxide, and hydrogen. Practically all the free oxygen is combined with iron as FeO. All these gases are almost entirely insoluble in solid steel and hence are evolved during solidification. Part of this gas is trapped in the crystal formation, producing cavities or blowholes. These holes are usually elongated in a direction perpendicular to the mold wall. In addition to the above-mentioned dissolved gases, carbon reacts with FeO to

produce CO during the time the metal is liquid and this reaction is an additional source of gas. Owing to the fact that low carbon steel is usually more highly oxidized than high carbon steel, blowholes are much more common in low carbon steel, where this reaction produces larger amounts of CO.

Since the gases evolved are neutral or reducing in nature, the surfaces of the blowholes are usually not appreciably oxidized when they are deep in the interior and generally can be welded satisfactorily during the fabricating operations. Furthermore, the presence of the blowholes increases the apparent volume of the metal and in this way partly compensates for the shrinkage of the metal on solidification. This produces a decrease in the extent of the shrinkage cavity and, when large amounts of gas are evolved, causes the metal to rise in the mold. The decrease in the shrinkage cavity, owing to the formation of blowholes, accounts for the fact that steelmakers hesitate fully to deoxidize carbon steels containing over 0.25 per cent carbon when casting them in big-end-down molds. Complete deoxidization increases the size of the cavity and decreases the yield per ingot.

The position of blowholes in the ingot is of great importance, as it has a decided effect on the finished product. Blowholes deep under the surface are not considered particularly detrimental but, when near the surface, they may cause serious difficulties. During the rolling operations, blowholes near the surface may break out, *i.e.*, the metal between the surface and the blowhole may crack. This allows the surface of the blowhole to be oxidized and prevents it from being welded shut by subsequent pressure. Also, if the blowholes are close enough to the surface, oxidation of the entire ingot surface may scale off enough metal to expose the blowholes. The oxidized blowholes are elongated by rolling into long surface seams or other defects which require subsequent expensive chipping of the billets to remove them.

The quantity of blowholes is controlled largely by the extent of deoxidation and degasification of the steel and the rate of solidification. Their position is, however, dependent upon a number of factors, among them being the composition of the metal, teeming temperature, rate of solidification, and mold design.

Inclusions.—Nonmetallic inclusions or "sonims," as they are often called, enter the steel from a number of sources. The products of deoxidation are the principal source of inclusions in

the steel and of these, SiO_2 and Al_2O_3 are probably the most numerous. Both these oxides are insoluble in the steel, highly infusible, and form very small particles which rise through the liquid steel only with difficulty. In addition, they are formed rather late in the steelmaking process and hence have only a limited time in which to be eliminated from the metal. When aluminum is added to the mold, probably very little of the Al_2O_3 escapes to the top before the metal solidifies.

Nonmetallics also enter the steel from the furnace slag, the hearth lining, and the ladle lining. In case the ingot is bottom-poured, there is danger that the steel will wash pieces of the runner bricks into the mold. Considerable caution is required to keep inclusions from entering the metal from these sources.

The dangers resulting from the presence of inclusions depend to a large extent upon their distribution in the metal. If they are uniformly distributed or the majority rise to the top of the ingot during its solidification and are subsequently cropped off, their presence is not particularly serious. The inclusions tend, however, to segregate (accumulate in certain portions) and form a serious defect when that occurs. A point at which inclusions have segregated is often the starting point for an internal crack in the ingot, which is particularly dangerous because it is difficult to detect. Sonims are always a potential source of weakness in steel because they break up the unity or continuity of the metal merely by their presence.

The presence of sonims in the ingot can be largely eliminated by proper deoxidation and pouring procedure. The heat can be made clean and kept clean by carrying out the deoxidation in the furnace, or as much of it as is possible; by using double deoxidizers in the ladle and allowing plenty of time for the products of deoxidation to rise into the slag; by avoiding the use of aluminum in the molds; and by carefully patching the ladle and furnace linings. The presence of inclusions is serious enough to call for limiting specifications as to their amounts in quality products.

Ingotism.—The formation of very large crystals is called *ingotism* and is the result of very slow cooling during solidification. The slower the rate of cooling, the larger the individual crystals can grow because they have a longer time in which to increase in size.

A large crystal formation is a source of weakness for two reasons. In the first place, large crystals are inherently weak and are apt to tear during rolling and cause defects in the finished products. A coarsely crystalline ingot must be very carefully handled during the first few passes and only small reductions

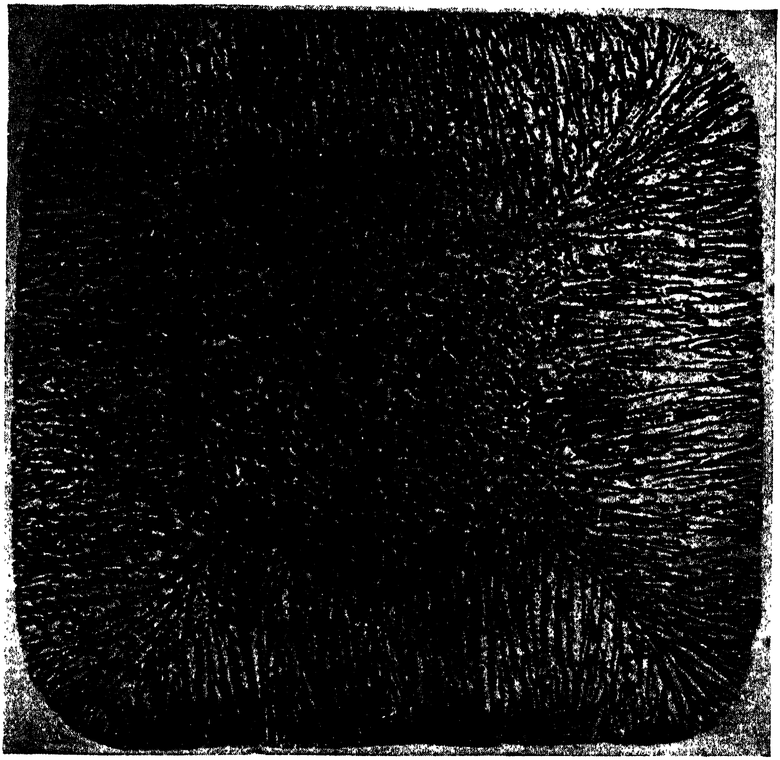


FIG. 16-VII.—Horizontal fracture of a steel ingot showing dendritic structure. Note the central pipe. (*Courtesy of The Gathmann Engineering Co.*)

can be used or tearing will result. These large crystals are broken up during rolling by the pressure of the rolls and smaller crystals form which do not have the dendritic characteristics of the large ones. The effects of ingotism on the final products obtained from the ingot are removed in this way.

In the second place, the manner in which the crystals are "oriented," or the directions in which they grow with respect to the mold walls, often causes planes of weakness in the ingot

which will result in cracks unless the ingot is carefully handled in the mill. It has been shown before that the crystals grow most rapidly in a direction perpendicular to the mold walls. If a mold is used that is rectangular or square in cross section, the crystals growing out perpendicular to two adjacent walls will meet, forming a plane of weakness or cleavage at an angle of 45 deg. to both walls, as shown in Fig. 16-VII. This type of crystal growth continues until the chilling effect of the mold walls is entirely lost. This effect is intensified at the bottom of a square bottom ingot where the crystals growing upward from the bottom meet the crystals growing inward from the sides just above it. The junctures of these three sets of crystals along lines running from the bottom corners up into the body of the ingot are serious points of weakness and often result in the familiar butt cracks in the rolling mill.

The growth of large crystals can be minimized by rapid solidification of the metal and a low teeming temperature, although there are definite limits to these methods. Various modifications in the shape of ingot molds have been used to prevent the planes of weakness described above. These changes will be covered later.

Segregation.—Segregation in ingot structures is the concentration of the metalloids—carbon, manganese, phosphorus, and sulfur—in proportionately greater amounts in certain parts of the solid ingot than in other parts. When steel crystallizes in an ingot mold, there is a continual rejection of the more fusible impurities which therefore tend to concentrate in that part of the ingot which solidifies last, which is the center or upper central part of the ingot. In killed steel ingots it is found that segregation is slight as compared to the open or rimming steels. The process by which segregation takes place and the general differences as encountered in killed and open or rimming steels will now be discussed.

Killed Steel.—When a killed steel ingot is first teemed, the metal contacting the cold mold walls will have a rapid rate of solidification and, since it is rapid, the first layer will not be appreciably segregated, *i.e.*, its analysis will be approximately that of the liquid steel as teemed. Immediately following this short period, the rate of solidification drops rapidly and segregation will begin, the metal now freezing being purer than the liquid

steel as teemed. The rate of solidification continues to decrease, with the result that more and more time is given for the steel solidifying at the surface to be selective, *i.e.*, purer than the analysis as teemed. Since killed steels are quiet, the solidifying steel pushes the rejected material ahead of it into the main body of the liquid metal. The remaining liquid metal has during this time become more and more impure, and eventually a point is reached where the solidifying metal is more impure than the metal as teemed. From this point on, the solidifying metal becomes increasingly impure as the ingot becomes solid. In killed steels, therefore, the amount of segregation changes quite uniformly from the outside to the center of the ingot. This uniformity of segregation is also aided by the formation of dendritic crystals which tend to trap the rejected material in their branches.

Some of the factors that influence segregation in killed steel ingots are as follows:

1. Mold sizes. The larger the cross section the greater the amount of segregation.
2. Pouring temperature. Normal temperatures usually give least segregation; cold heats especially give excessive segregation.
3. Hot-top volume. Too small volume gives more segregation and pipe; too much hot-top volume is a waste of steel.
4. Mold design. Such items as amount of taper have an influence on the amount of segregation.

Rimmed Steel.—In the production of rimming heats, one of the chief difficulties is the unavoidable excessive segregation and increase of nonmetallic inclusions. Carbon and sulfur particularly have a bad tendency to segregate, considerably more so than they do in fully deoxidized and semideoxidized steels.

In general, it will be found that all the elements segregate with the rim zone slightly lower than the ladle analysis from top to butt of the ingot. The core zone, however, segregates in much the same manner as killed steel but to a much greater degree. The change in analysis from rim to core is quite abrupt and will occur within a space of as little as ½ in. of the ingot cross section.

Surface Defects. *Slivers.*—Slivers result from tears. They occur on the ingot surface as a scablike defect which is not welded to it because of the oxide film surrounding it. There are a number of factors causing this defect, such as rough mold surface which

hinders the contraction of the ingot, overheating in the soaking pit, twisting in the rolls, and occasionally guide marks. Rolling action, and to some extent rolling temperature, is the principal cause for slivers on steels which tear easily in the heavier drafts. Steels below about 0.25 per cent carbon with very porous surfaces containing numerous blowholes are very susceptible to this defect. Slivers resulting from blowholes are usually light and are in most cases removed by one chip. Slivers very frequently occur along with seams which have resulted from the elongation by rolling of numerous small blowholes and pits which occur on or near the

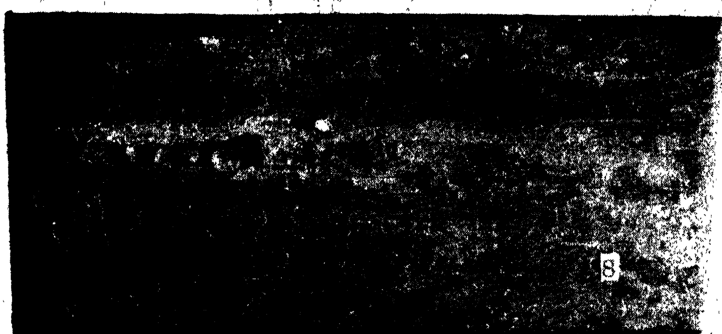


FIG. 17-VII.—Slivers.

surface of the ingot. This combination is usually encountered on products rolled from rimmed and capped ingots which have undesirable mold action. Figure 17-VII illustrates the general appearance of this defect as developed on a 4 by 4-in. billet.

Scabs.—Scabs are defects that originate through imperfect nozzle conditions when pouring, from bottom splashes from deeply grooved stools, or from the splash and spray brought about by the stream striking the molten metal in partly filled molds (see Fig. 18-VII). The patches of metal splashing against the mold wall tend to stick to the mold where they quickly solidify and acquire an oxide film. The scabs are then formed when the rising metal in the mold comes in contact with the patch where a part or all of it adheres to the thin skin where it remains in the solidified ingot. Upon subsequent rolling,

the loose scabs are either broken from the surface or rolled into the surface where they must be removed by chipping.

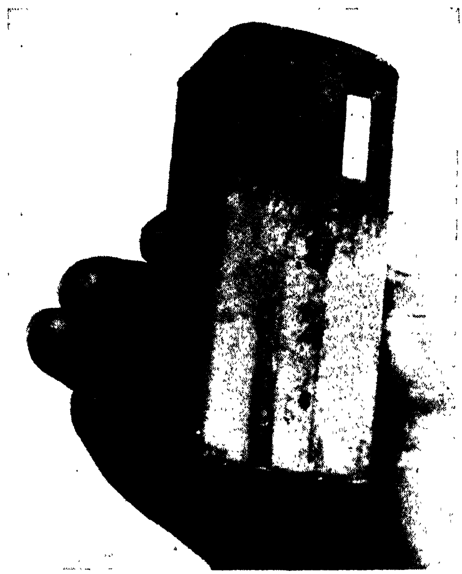


FIG. 18-VII.—Scabs from bad mold condition.

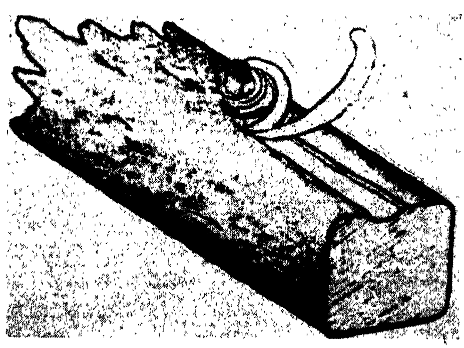
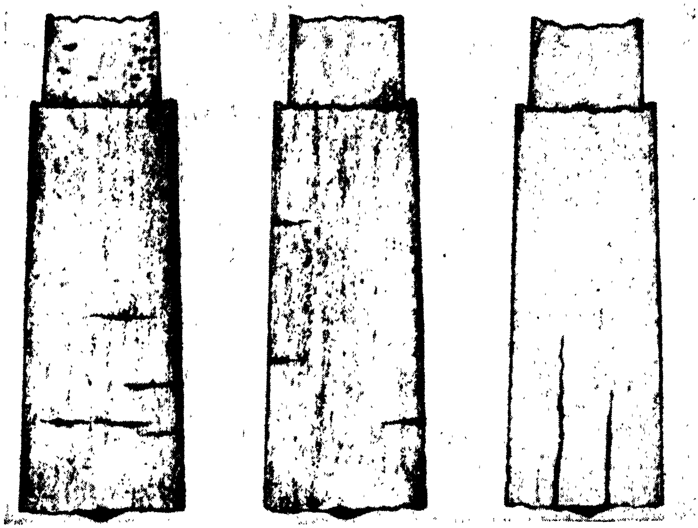


FIG. 19-VII.—Lamination. (*Courtesy of C. R. Lynch.*)

Laminations.—This very serious defect is caused by the rising metal in the mold entrapping splashes below the surface of the ingot. On subsequent rolling the formation is elongated into a fibrous longitudinal structure. The structure is lamellar in character, hence the name lamination for the defect. When this

defect is uncovered by chipping, it comes off in a double chip (see Fig. 19-VII). It is readily recognized, as the fibrous structure is always peculiarly discolored from a yellowish-gray powder which has been identified as being principally iron oxide.

Laminations are often found associated with scabby surface, but this is not always the case as some steels having scabby surface contain no lamination; the steel may also be free from scabby surface and still contain serious lamination. Because of its subsurface formation, laminations are dangerous and diffi-



A B C

FIG. 20-VII.—*A*, transverse cracks; *B*, corner cracks; *C*, vertical cracks. (*Courtesy of C. R. Lynch.*)

cult to detect. If disclosed, the defect may be removed by chipping unless it extends too deep when it may warrant scrapping the product. If not detected, it usually results in scrapping the finished product.

Cracks.—Cracks in the surface of an ingot are due to such factors as mold design, mold temperature, pouring temperature, fluidity of the steel, chemical composition, and pouring methods. The effect of differential cooling of the inside and outside of the ingot and of the expansions and contractions of the mold and ingot in setting up highly stressed conditions which may lead to cracks has been previously discussed. It is found, particularly

in killed steels, that the lower third of the ingot is more susceptible to the formation of planes of weakness and it is within this area that the greatest number of cracks occur.

Cracks occur as transverse, corner, and occasionally vertical (Fig. 20-VII *A*, *B*, *C*). Transverse cracks are the most common ones and are developed by rolling into three distinct types. The distinction among the types lies in their original location and shape in the ingot and the amount of deformation effected by the rolling. The seam may result from either a transverse or a vertical crack which on rolling becomes a longitudinal fracture on

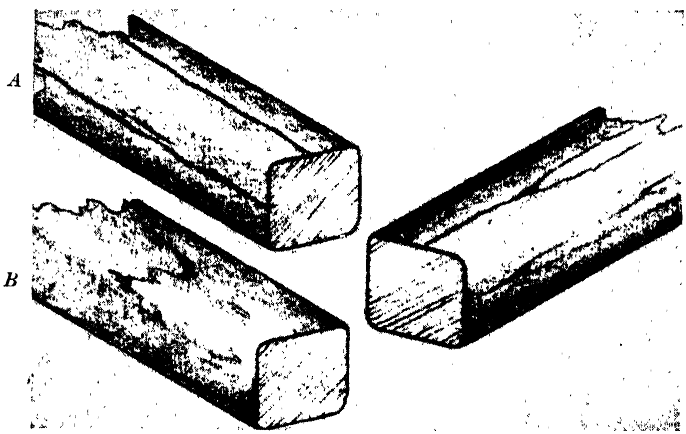


FIG. 21-VII.—*A*, heavy seams; *B*, flaws; *C*, church steeples. (*Courtesy of C. R. Lynch.*)

the surface (Fig. 21-VII *A*). The flaw is caused by corner and transverse cracks that have not been greatly affected by the rolling action. They develop into a jagged fracture (Fig. 21-VII *B*). The third type is formed from a transverse crack which in the rolling has been greatly elongated into a double seam joining at one end and extending further as a single seam (Fig. 21-VII *C*).

These defects are not usually troublesome unless they are numerous and of considerable depth, in which case the product is scrapped. They are easily detected and may be chipped without difficulty.

INGOTS AND INGOT MOLDS

Most ingots used in present-day practice are rectangular in section with rounded corners. Rectangular sections are pre-

ferred to square ones on account of their increased rate of solidification with a resultant decrease in segregation. In the special and alloy steel shops, however, the type most generally used is the round corrugated ingot.

Ingot molds are usually made of cast iron with an approximate analysis as follows: total carbon, 4.00 per cent; manganese, 0.90 per cent; silicon 1.50 to 1.75 per cent.

The ordinary life of a mold varies from 75 to 150 heats. This wide variation is dependent upon the type of mold (slab or square), the kind of steel poured, the stripping facilities, and the time of stripping. A mold may be used for the first 50 heats on a high-grade product and then used for a lower quality product, thereby increasing its useful life. It has been shown that molds for special steels should be discarded before they have heat-checked too severely, as heat checks help to produce surface imperfections and, if present, result in high rejection and increased chipping costs.

Common mill ingots range in weight from 8,000 to 48,000 lb., with the largest tonnage ranging from 12,000 to 15,000 lb. Ingots of killed and semikilled steel are poured to an average height of 80 in., although in some cases they go as high as 92 in. Rimmed steel ingots average between 70 and 72 in.

Typical ingot molds used for different classes of rolled products are shown in Table 1-VII.[1]

A considerable amount of investigation has been done and is being done in an attempt to perfect an ingot mold that will eliminate the above-mentioned defects and at the same time will be cheap, will produce an ingot easy to handle in the rolling mill, will have a long life, and will be easy to cast. A mold that will fill all these requirements has not yet been constructed, but several important improvements have been made over the old rectangular, big-end-down design. It should be emphasized again, however, that no matter how good the mold design, a good quality of ingot cannot be obtained without proper steel-making and teeming practice.

The present-day big-end-up mold, equipped with a hot top, is probably the best method of combating most of the internal defects in killed steels. This mold was not designed at once

[1] Bent, Q., Modern Rolling-mill Practice in America, *J. Iron Steel Inst.*, **138**, No. 11 (1938).

but is the result of a slow evolution from an inverted big-end-down design. This mold, by inducing solidification from the bottom up, concentrates the pipe and badly segregated portion in the sinkhead and minimizes, if it does not eliminate, porosity. The rounded bottom prevents, except in rare cases, the formation of bottom corner cleavage planes which are the cause of butt cracks.

TABLE 1-VII

Size of mold, in.	Style	Grade of steel cast	Quality of steel cast	Approximate weight of ingot, lb.
20 × 24 × 84	Straight faced	Structural	Semikilled	8,900
21 × 41 × 80	Corrugated	Sheets	Rimmed	17,200
25 × 30 × 86	Corrugated	Rails and rods, hot-pack tin plate	Killed	13,840
25 × 30 × 86	Straight faced	Rails	Killed	14,300
26 × 50 × 84	Corrugated	Plates and hot strip	Rimmed and semikilled	24,000
28 × 90 × 92	Inverted* corrugated	Plate	Killed	48,200
28¾ × 53 × 84	Inverted* corrugated	Plate	Killed	25,700
Round 24 × 77	Inverted* corrugated	Alloy and special bars	Killed	6,800
28 × 35 × 90	Corrugated	Structural	Semikilled	20,500

* Inverted big-end-up.

The shape of the cross section of the mold has undergone radical changes in the last twenty years for certain classes of work. Changes in the design of mold cross section have nearly all been the result of attempts to improve the surface quality of the ingots, particularly the prevention of surface cracks and ruptures of the skin during solidification and the prevention of surface cracks during the early stage of rolling.

Three principal factors should be considered in the proper design of mold cross sections:[1]

[1] GATHMANN E., "Ingot Contour," Gathmann Engineering Co., 1930.

1. The mold must be so shaped that the ingot skin is free to solidify without binding or hanging to the mold walls and to contract inwardly with a minimum of surface stress.

2. The corners of the ingot must not have such sharp angles that they (*a*) will easily become overheated and decarburize in the soaking pits, (*b*) will develop corner cleavage planes due to dendritic crystallization, or (*c*) will overlap during the first rolling operation.

3. The shape of the solidified ingot must be such that it can be reduced in the rolling mill or forge without either overworking the corners or tearing the free sides during the initial passes.

These factors require some explanation. When the ingot skin solidifies, it shrinks in all directions. If the mold has straight sides, the skin cannot be deformed without stretching and consequent danger of cracking. If the ingot cross section has a slight inward curvature, however, this tendency is resisted. This curvature also helps to support the skin and prevent the liquid interior from breaking through the skin. A corrugated mold wall is the usual means of carrying this out.

When the ingot is soaked in a gas-fired pit furnace, sharp corners are apt to become overheated. This causes the carbon to be oxidized out of the metal at these corners, sometimes producing severe decarburization and hence a nonuniform carbon distribution in the ingot. Furthermore, when a sharply corrugated ingot is rolled, the protruding corrugations are apt to be laid over on the adjacent metal rather than pressed down flat as they should be. This lapping over of the corrugations produces seams running lengthwise on the surface. We have also seen that sharp corners cause the formation of planes of weakness. For these reasons, the ingot corners must be gently rounded.

As the ingot is passed through the rolls the first time, the two opposite sides of the ingot in contact with the rolls are worked and compressed toward each other. This action causes a lengthening of the ingot in the direction of rolling and breaks up the large crystal formation close to these surfaces. The two sides of the ingot not in contact with the rolls are not worked but are elongated with the rest of the metal. Since large crystals are much weaker than small ones, the large, unbroken crystals in the unworked sides often tear apart when stretched and cause

surface cracks. Also, if the two sides that are worked first are too severely compressed, they are likely to develop cracks. The cross section of the ingot should be such as to minimize these difficulties.

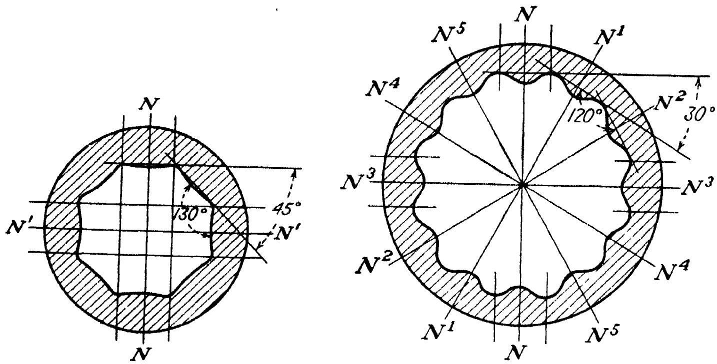


FIG. 22-VII.—Examples of cross sections of round corrugated molds. (*Courtesy of The Gathmann Engineering Co.*)

Practically all recent ingot mold designs employ corrugations in some form or other. Their primary object is to increase the perimeter of the cross section of the mold. The larger the perimeter of the ingot, the faster will be the rate of cooling and solidification of the ingot skin (all other factors being the same). Corrugations, therefore, by increasing the surface area of the ingot, increase the rate of solidification of the skin and ensure a smaller crystal size near the ingot surface. We have also seen that corrugations help to prevent skin ruptures during solidification.

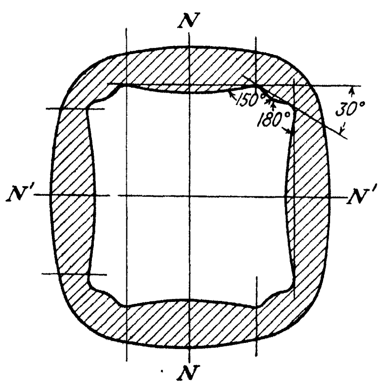


FIG. 23-VII.—An example of a rectangular corrugated mold. (*Courtesy of The Gathmann Engineering Co.*)

Two types of corrugated molds are in general use. One has a round cross section modified by corrugations, and the other type has a square or rectangular cross section, modified to meet the general requirements of mold cross section outlined above.

Examples of the modified round or "fluted" mold are shown in Fig. 22-VII. The principles discussed above are present in both these designs but they have certain drawbacks. Ingots from these molds require more soaking pit capacity and more mill passes than rectangular or square cross-sectioned ingots. The plant output is lessened, and for this reason these molds are rarely

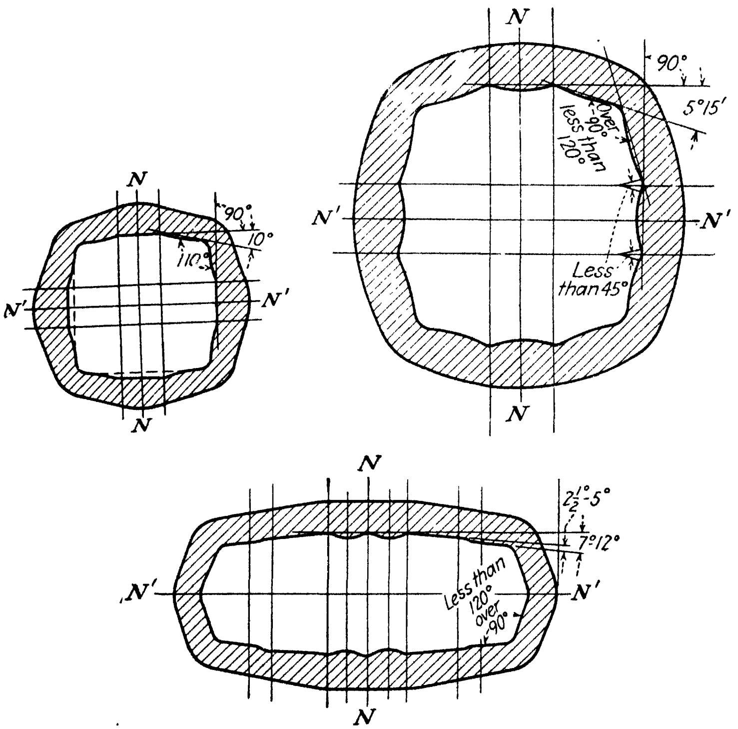


FIG. 24-VII.—Examples of mold contours. (*Courtesy of The Gathmann Engineering Co.*)

used except for forgings. They are widely used for forging work where more care can be taken in fabrication. The round corrugated mold has become the standard for large gun forgings.

In the design of rectangular molds with corrugations, care should be taken to keep the corner angles from being too sharp. Also, the corrugations should be kept relatively flat or they will overlap during rolling. Figure 23-VII shows a type that has been in use for some time. When an ingot from this type of mold

is first rolled on the narrower surfaces N-N, the other two principal sides are not appreciably worked and the ingot can be squared up without cracking. More recent designs are shown in Fig. 24-VII. In all these designs, the initial pass in the rolls swages the metal sideways rather than in the direction of rolling, at least until the surface is flat. This produces grain refinement in these faces without stretching the other two faces unduly. When the next pass is taken on the previously unworked faces, the grain of the worked faces is sufficiently refined to withstand elongation without rupture.

It should be understood that these corrugated contours are used when the specifications on surface defects are rigid and that the ordinary mill ingot is still cast square or rectangular in cross section with rounded corners. It is believed that the present tendency is toward the designs discussed above, since they produce articles with better surfaces at slight if any increased cost when the decrease in chipping necessary to remove surface defects is taken into account.

PREPARATION OF THE INGOT FOR ROLLING

For an ingot to be properly fabricated by either forging or rolling, the metal must be at the proper temperature and the temperature of the mass must be uniform. As the ingot is stripped from the mold it possesses neither of these requirements and must be given a preliminary conditioning treatment before it can be worked. When the ingot is removed from the mold, the outside is cooler than the interior—in fact, big-end-down ingots are often stripped before they are entirely solid, particularly when made of the semideoxidized class of steel. This unevenness of temperature must be removed by soaking the ingot in a pit furnace, called a "soaking pit," until it is entirely solid and at a uniform and desired temperature. If rolling is started before the metal has entirely solidified, the interiors of the bloom or billet will be porous, causing a serious defect called a "coky" center. The soaking treatment also tends to decrease segregation by diffusion of the segregated constituents.

If the ingot is not to be rolled within a short while after stripping, it is buried in ashes, sand, or other material of poor heat conductivity and allowed to cool very slowly. This precaution is necessary as the strains produced by the cooling of such a large

mass of metal are quite severe and, unless the metal is very slowly cooled, serious cracking results. After cooling, the ingot is stored until required and then very slowly heated to the desired forging or rolling temperature over a period of from 8 to 10 hr. As this procedure is expensive and hazardous, owing to the dangers of cracking, it is done only when it is absolutely necessary. The mills and soaking pits are usually designed to take the entire output of the various melting furnaces without overloading them. Sometimes, however, a breakdown in the mill necessitates the storing of ingots.

Soaking pits, as originally designed, were merely brick-lined holes in the ground provided with tightly fitting covers, in which the ingots were placed. The heat contained in the metal was supposed to heat the pit and maintain the ingots at the desired temperature.

The furnaces used today are of three different designs: (1) the reversing regenerative type of pit, (2) the one-way fired recuperative pit, and (3) the circular nonregenerative pit. The last two types of pits are fundamentally new designs from the most widely used reversing regenerative type. The one-way recuperative pit employs a simple single flow, where the flame enters at one end and leaves the same end at a lower level taking a U-shaped course in its travel and no reversing is necessary.

In the circular nonregenerative type of pit, the flame enters from the center of the pit bottom or tangentially around the side of the hole. The reversing regenerative type of pit operates very much the same as the regenerative system in the open-hearth furnace with the exception that the periods of reversals are usually much longer.

A cross section through the underground portion of a soaking pit is shown in Fig. 25-VII. The air and gas regenerators are placed below and on each side of the soaking pit itself. The fuel used in the different types of installations varies considerably, dependent to a large extent on availability and cost. Some of the different mixtures are straight by-product coke-oven gas, blast-furnace and natural gas mixed, producer gas, blast-furnace and coke-oven gas, oil, blast-furnace gas straight, etc.

The pit that holds the ingots is constructed of firebrick with a few courses of chrome brick just above the floor level as a protection against the oxide scale on the ingots. This scale is

liquid or nearly so, drips off the ingots, and would corrode an acid refractory badly if it were allowed to come in contact with it. A thick layer of coke dust is spread on the bottom of the pit to produce a reducing atmosphere in the pit and minimize scaling. A heavy, brick-lined steel cover is provided for the upper opening of the pit. The cover is equipped with wheels which run on a track laid on each side of the pit. The cover is moved by either an electric motor or a hydraulic piston.

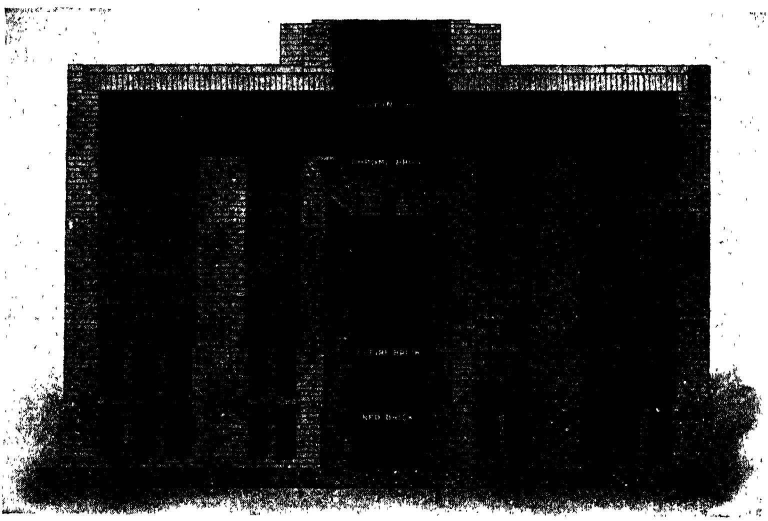


FIG. 25-VII.—Cross section of a four-hole soaking-pit furnace. (*Courtesy of Harbison-Walker Refractories Co.*)

As the procedure is usually carried out, the molds and ingots are separated from each other by the stripper and the ingots transported on cars to a soaking pit. An overhead crane, equipped with tongs, is used to transport the ingots to and from the soaking pit. The ordinary pit is designed to hold from 6 to 12 ingots (varying at different plants). The ingots are placed upright in the pit and spaced in such a way that all sides are heated evenly and yet the flame does not strike them. When an ingot is sufficiently soaked, it is removed and transported to the mill for rolling or forging (see Fig. 26-VII).

The temperature at which the ingot should be withdrawn for rolling depends upon the composition of the steel and how much

hot work is to be done before the piece is reheated. The actual rolling temperatures are between 1950 and 2300°F., depending upon the above factors. The power required for fabrication is dependent upon the ease with which the metal can be deformed. The higher the temperature at which the metal is rolled, the easier it will deform and the less the power required. On the other hand, it should not be heated enough to begin to melt. Furthermore, when ingots are rolled too hot, they are likely to crack unless very carefully handled. In order to save power and

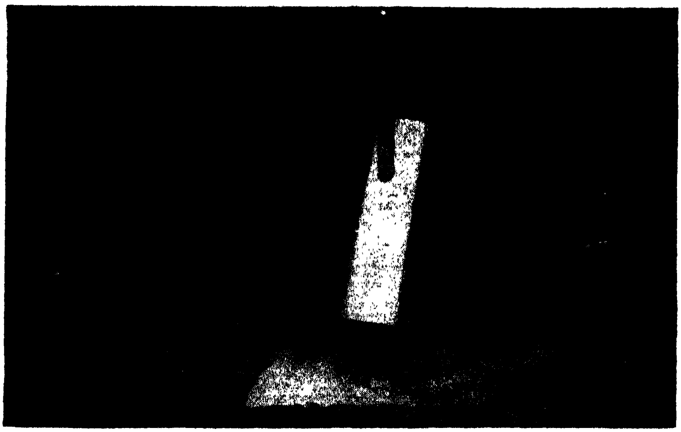
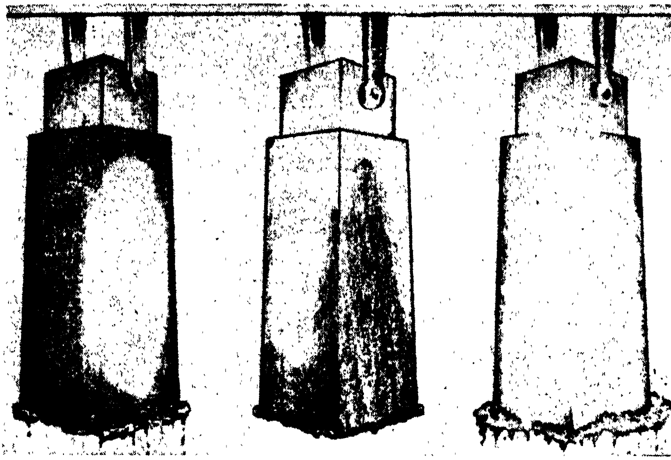


FIG. 26-VII.—Placing an ingot in the soaking pit. (*Courtesy of Jones & Laughlin Steel Corp.*)

wear and tear on the rolls, ingots are usually rolled at as high a temperature as possible without overheating the metal. This is not entirely consistent with the best results obtainable, as will be seen later, but it is the practice usually followed.

HEATING DEFECTS

The heating of ingots in the soaking pit must be done very carefully, as frequently the temperatures reach very near the burning point. This care in the heating is necessary so that the ingot surfaces and particularly the corners will not be overheated or burned. Abnormal heating conditions will range from cold or unevenly heated ingots (Fig. 27-VII-*B*) which are difficult to roll, to ingots that have been burned so badly in the heating that the portions so affected will break badly on rolling and must usually be scrapped. These conditions are the result of erratic gas reversals in the pits. When the ingots are drawn from the pit before



A B C

FIG. 27-VII.—*A*, port marked; *B*, uneven heat; *C*, washed ingot. (*Courtesy of C. R. Lynch.*)

FIG. 28-VII.—Burned corners.

the oxide coating has been melted, they are called "port marked" and are very hot on the side nearest the flame (Fig. 27-VII-*A*). If the ingot were heated for a considerably longer period under these same conditions, it would develop "nipped corners" or become "washed," which condition is due to the oxide or scale becoming liquid and running down the sides (Fig. 27-VII-*C*). Washing of an ingot is not always undesirable as some steels must be heated to very high temperatures that will be above the melting point of the oxide. Special attention must be given in these cases so that the heating will be uniform without excessive washing on any one side. Excessive washing that causes the burning of the surface or corners brings about a very brittle condition in the portions affected. No subsequent heat-treatment will rectify this condition and upon subsequent rolling the affected portion will break very severely (Fig. 28-VII).

Uneven heating of the ingot causes uneven reduction in area on subsequent rolling and often leads to the formation of mechanical defects. Uneven heating also leads to the formation of slivers and tears in some types of steel.

Suggested Questions for Study and Class Discussion

1. What is the first thing that happens when molten metal is teemed into an ingot mold? In what direction does crystal growth occur? What causes the rate of cooling to be retarded when steel is undergoing solidification in the ingot mold? When molten steel solidifies, what volume change takes place? What is the effect of this volume change upon the interior of an ingot cast into a big-end-down mold?

2. What is the function of the hot top?

3. What is pipe? What causes it? Why does pipe extend so far down in a big-end-down ingot? What is secondary pipe? How can secondary pipe be avoided?

4. What are blowholes? What causes them in an ingot? Why do we have more blowholes in low carbon steel ingots? What happens to blowholes during rolling when blowholes are (*a*) deep seated, (*b*) near the ingot surface, or (*c*) very near the ingot surface? What determines the position of blowholes in an ingot?

5. What is ingotism? In what two ways can ingotism be a source of weakness? What is segregation? What are slivers? How are scabs formed?

6. What causes ingot cracks? What types of defects are formed by rolling cracked ingots? How has mold design been improved to avoid cracking of the ingot skin during solidification? What is the object of corrugations in an ingot?

7. What is the function of the soaking pit? What governs the temperature to which ingots are heated for rolling, and why?

CHAPTER VIII

THE FABRICATION OF STEEL

PRINCIPLES OF FABRICATION

The vast importance of the fabricating processes in our present-day civilization can be easily visualized by a study of the production figures given in the iron and steel trade journals which show that millions of tons of steel ingots yearly are mechanically shaped to the desired final form and size. This immense amount of metal is fabricated into a bewildering variety of products of practically every size and shape, from a large naval gun to an ordinary pin. Practically everything with which we come into daily contact is either a fabricated steel product or made by the use of fabricated steel. The purpose of this chapter is to discuss the principles underlying the fabrication processes as a preface to a description of the methods of carrying them out.

Some indications of the reasons for fabrication were given at the beginning of the preceding chapter, but we shall go a little more into detail here. When steel parts of a certain final size and shape are produced, a choice must always be made between casting the parts into desired shape and size directly and shaping them mechanically from a simple cast shape (an ingot). This choice will depend upon the cost of production, the size and shape of the finished part, and the purpose for which it is intended. Some parts must be made by mechanical means because the service for which they are intended demands the superior physical properties obtained only by fabrication. Other products can be made only by casting because they are either too large or too intricate in shape to form by mechanical means. Between these two extremes lie a large number of different parts which could possibly be made by either method. The choice then will depend upon a balance between cost and quality. A well-made fabricated part is of better quality than an equally well-made casting of the same composition. Castings are usually cheaper to make unless they are very small or a great many are to be made.

The primary object of fabrication is to obtain steel products of a desired final size and shape. Of equal importance is the effect of mechanical shaping on the metal. This will be taken up in detail in connection with the various methods of fabrication but the general effects can be indicated here. The physical properties such as strength and ductility are increased, blowholes are closed, porosity is eliminated, segregation diminished, and the size of the crystals decreased. All these factors make for better quality of the finished product, and the fabricated part is a distinct improvement over the ingot in these particulars. Since a steel casting possesses the same internal structure as an ingot and is heir to the same defects (as well as others) but to a smaller degree, the better properties of fabricated steel parts can readily be understood. It is true that heat-treatment of castings diminishes the difference between the properties of cast and mechanically shaped parts of the same composition, but if the same heat-treatment is given both types of material, the difference between them is well in favor of the fabricated part.

Steel possesses several properties that make it possible to use fabricating methods in fashioning articles from it. It is not to be inferred that only steel possesses these characteristic properties or even that steel possesses them to a greater degree than other metals, but that these properties are of great value to all substances that are to be mechanically worked.

The first of these is *malleability*. This has been defined as the capability of a metal of being permanently deformed without rupture by pressure, as by hammering or rolling. A common measure of malleability is the thinness of sheet that can be produced from a metal by hammering or rolling. Since malleability is dependent upon the property of plasticity to a considerable extent, the malleability of a metal generally increases with increase in temperature of the metal. When a metal is malleable at ordinary but not at high temperatures, it is said to be "red short" or "hot short." When the reverse is true, it is said to be "cold short."

Pure iron ranks ninth among the metals in degree of malleability, gold being the most malleable metal known. Owing to the elements that it contains in addition to iron, steel is not so malleable as pure iron. The degree of malleability of steel is dependent upon the amount and physical condition of the

impurities and alloying elements contained in it. In general, the malleability at any one temperature decreases as the amount of impurity is increased. The degree of malleability of steel is of considerable importance in fabrication as it determines the extent to which the working of the piece can be carried as well as the power required for the fabricating operations. If a metal is compressed beyond its capability to deform, it will crack. Also, the power required for compression increases with decrease in malleability of the metal.

Heat content and *heat conductivity* are of importance when working a metal while hot. The heat content of a metal is defined as the number of units of heat (B.t.u.) contained in the metal per pound at any definite temperature. The higher the temperature of a metal, the greater its heat content. The more heat a given piece of metal contains at a given temperature, the slower it will cool from that temperature (other factors being equal) and the longer the piece can be worked without reheating.

By heat or thermal conductivity is meant the rate at which heat is conducted in the metal from a hotter to a cooler portion. This factor, then, affects the ability of a metal to maintain a uniform temperature during fabrication. When the piece comes in contact with a cold roll, for example, the metal in contact becomes chilled by losing heat to the roll. When this contact is broken, ordinary steel rapidly regains heat by conduction from the interior. Most metals and alloys have fairly high heat contents at high temperatures and good thermal conductivity. The thermal conductivity of steel is quite appreciably lowered by the addition of large amounts of alloying elements. Both of these properties are of importance in reheating operations during fabrication and will be further discussed in this connection a little later in the text.

Finally, the *crystalline structure* of steel is very important in fabrication. Mechanical work, in general, reduces the size of the crystals, or, as it is called, "refines the grain." The grain (crystal) size of the piece is carefully watched throughout the production of quality products because, unless this factor is considered, serious difficulties often arise. Noncrystalline materials are usually plastic when hot but brittle and hard when cold. If steel were not crystalline, it is very probable that it could not

be worked when cold. This branch of fabrication is very important, incidentally, and many products could be produced only with considerable difficulty if steel could not be cold-worked.

There are two main subdivisions into which fabricating processes are divided: hot working and cold working. Each of these methods has a definite place in the general scheme of fabrication and each produces a different effect upon the metal. As their names imply, the difference between them is based upon the temperature range within which the mechanical work is carried out. In the case of many metals and alloys, these two divisions are merely relative. By hot working is meant working at red heat where the metal is relatively plastic; by cold work is meant working of the metal at a relatively low temperature. In the case of iron and steel, however, the situation is different as the temperatures of hot working are influenced by a transformation in the metal itself which will now be described.

At all temperatures between about 1650°F. (899°C.) and its melting point (except for a short range just below the melting point with which we are not concerned here), pure iron exists in a crystalline form known as "gamma" iron. The arrangement of atoms in this type of structure may be described by imagining a cube with an atom of iron placed at each of the eight corners of the cube and six other atoms at the centers of each of the six faces of the cube. This is commonly known as the "face-centered cubic" structure and is possessed by other metals besides iron—nickel and copper, for example.

At a temperature of about 1650°F. (899°C.) on very slow cooling, pure iron undergoes a transformation involving a rearrangement of the atoms in the lattice. The new structure resulting from this change may be described by imagining a cube with an atom at each corner as before and with one additional atom placed at the exact center of the cube. This form is known as "alpha" iron and the structure is called "body-centered cubic." The reverse change from alpha to gamma iron can be brought about by very slowly heating the iron through the above temperature (it actually occurs about 15°F. higher on heating). This rearrangement is called an "allotropic" transformation and results in the formation of an entire new set of grains. By this is meant that when either of the forms changes to the other, the atomic rearrangement wipes out the existing grain structure

and replaces it with an entirely new set of grains which are very small in size. This process is called "recrystallization" and the temperature at which it occurs is called the "critical" temperature. This new set of grains is able to grow very rapidly in size by consuming each other, in this way producing fewer but larger grains in place of the large number of very small grains. The actual grain size of the metal after the transformation is accomplished depends upon the temperature and the time the piece is held at that temperature. The higher the temperature and the longer the time, the larger is the grain size, other factors

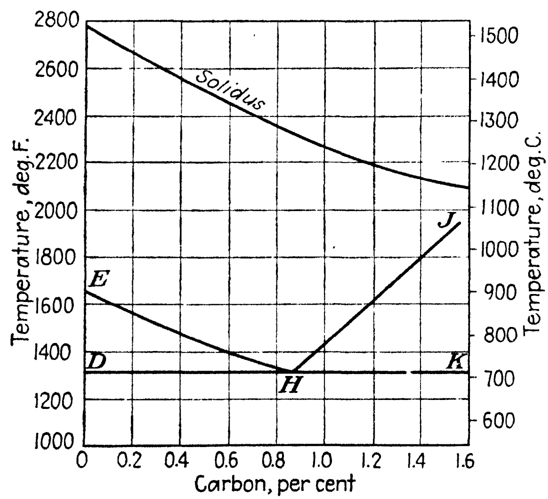


FIG. 1-VIII.—Critical ranges of steel of various carbon contents.

being equal. It is of interest to note in this connection that several other substances are allotropic besides iron, notably carbon, the two forms being graphite and diamond, and sulfur, the two forms being monoclinic and rhombic sulfur.

The addition of carbon or other alloying elements to iron causes this transformation to occur over a range of temperature instead of at the single temperature of 1650°F. The addition of increasing amounts of carbon causes a gradual lowering of the upper temperature limit of this range from 1650°F. to about 1333°F. (710°C.) at 0.87 per cent carbon. The lower temperature of this range between these limits of carbon content lies at a constant temperature of about 1333°F. As the carbon content is

increased beyond 0.87 per cent, the transformation involving recrystallization occurs at a constant temperature of 1333°F. Figure 1-VIII[1] shows the transformation range plotted as temperature against carbon content, for plain carbon steel. The further addition of other alloying elements may raise or lower both of these limiting temperature boundaries of the range or may raise one of them and lower the other, depending upon the element or elements added.

For our discussion here, we need not be concerned with the reasons for the changes brought about by additions to pure iron but we shall merely assume it to be true until later. A complete discussion of this subject forms one of the important parts of the third book of this series. The upper temperature boundary of the transformation range, extending in a smooth curve from 1650°F. at zero per cent carbon to 1333°F. at 0.87 per cent carbon (curve *EH*), is called the "upper critical" temperature for any given plain carbon steel. The straight line *DHK* extending from zero to 0.87 per cent carbon at 1333°F. is called the "lower critical" temperature for any given plain carbon steel. At higher carbon contents this distinction vanishes.

Hot Work.—Hot work may be roughly defined as the mechanical shaping or working of steel at temperatures where no permanent grain deformation occurs. The upper limit of hot working is dependent upon the carbon content since the temperature of the "solidus," as the line denoting the beginning of melting is called, slopes downward to lower temperatures with increasing carbon content. Pure iron melts at a constant temperature of about 2786°F. (1530°C.) while a plain carbon steel containing 1.5 per cent carbon begins to melt at about 2100°F. (1150°C.). The solidus is shown as the upper curved line in Fig. 1-VIII.

In actual practice, however, hot work is never started when the steel is at or just below the solidus because, while the alloy is theoretically all solid, impurities such as FeS, MnS, and certain nonmetallic oxides of low melting point may still be liquid or partly so. During hot-working operations, these pasty or liquid particles are elongated, producing defects because they break up the cohesion of the metal. Actual hot-working oper-

[1] This figure shows the transformations as they occur when carbon steels are very slowly cooled. Owing to temperature lag, these same transformations occur 20 to 30°F. higher with slow rates of heating.

ations are started at temperatures between 2300 and 1950°F., depending upon the carbon content. Special alloying elements also affect these ranges.

The pressure exerted on the metal by hot-working methods closes blowholes and welds them shut more or less completely if their surfaces are not oxidized; tends to eliminate porosity by compressing the porous open structure in the center of the ingot; and tends to equalize large differences in composition in some cases by the kneading action of the hot-working method. All these effects are beneficial to the steel and produce better physical properties in the finished articles.

The greatest single beneficial effect of hot working on steel is its effect on the grain structure. At hot-working temperatures, steel may be considered to be a solid solution of carbon in gamma iron. The carbon atoms may be thought of as being dispersed at random through the lattice of gamma iron and as being placed between the iron atoms. This produces a solid solution. Impurities present in the steel besides carbon and iron need not be considered here.

We have already seen that the ingot, before fabrication, consists of large crystals or grains of this solid solution, the grains near the outside being, in addition, oriented in a direction perpendicular to the mold walls. We have also seen that this effect produces lines and planes of cleavage or weakness and that the large gains throughout the ingot are a source of weakness in themselves. When these large grains are compressed by the hot-working processes, each grain is immediately broken up into a number of fragments, producing a strained condition in the metal. Owing to the relatively great mobility of the atoms at the high temperatures of hot working, this strain is immediately relieved by the formation of new small grains from the crystal fragments. The metal is strengthened by this process because the grain size is reduced and the grains themselves are no longer oriented in certain directions but have an entirely random arrangement. This latter change largely eliminates lines and planes of weakness. The small, newly formed grains are of approximately equal length in all directions and hence are often called "equiaxed" grains.

The newly formed small grains are free to grow in size and do so at a rate that is greater the higher their temperature and

the longer the time they have in which to grow at that temperature. Since hot working is almost never completed with a single application of pressure but is accomplished only with many successive applications of pressure, we can picture the grains of metal as being crushed, forming small equiaxed grains, growing to a larger size, and repeating the process with each subsequent application of pressure. The more frequent the pressure applications and the lower the temperature at which they are performed (but within the hot working range), the smaller the grain size of the metal will be at the finish of hot working. This is true because the more frequent the pressure applications the less time the new grains will have to grow between applications, and the lower the temperature at which the working is finished the slower the newly formed grains will grow. Also, the greater amount of hot work done on the piece the finer will be the grain size. Hot working usually should not be carried below the lower critical temperature because strains are introduced which harden the metal rapidly and their effects are removed only partly and relatively slowly.

During hot working the metal is cooling more or less rapidly. The larger its size and the smaller its surface area per unit of volume, the slower the piece will cool. Furthermore, part of the energy expended in the forming operations is converted into heat that serves to retard the cooling of the metal. In order to obtain finished articles with as small a grain size as possible, and hence as strong as possible, the temperature at which hot work is finished (the finishing temperature) is very important.

Steels containing less than 0.87 per cent carbon consist of a mixture of grains of pure alpha iron and grains of the solid solution of gamma iron and carbon (called "austenite") in the temperature range between the upper and lower critical temperatures. When the steel cools through its upper critical transformation, pure alpha iron (called "ferrite") starts to form from the austenite, producing the mixture referred to above, the ferrite forming as very small grains which grow if allowed to cool undisturbed. This continues until the lower critical temperature is reached where the remaining amount of the austenite transforms into a different and much harder constituent. Between these critical temperatures, both constituents of the steel can be deformed by

working, and they will reform in smaller grains which grow to larger sizes, although comparatively slowly at these temperatures. Working in this range causes the grains of the two constituents to arrange themselves in bands extending in the direction of working. This banded structure is not detrimental to the properties of the finished article in most cases, since the grains remain approximately equiaxed, and the grain size of the finished piece is smaller than if hot work were stopped above the upper critical range where the steel is composed of only one constituent. If hot work is continued below the lower critical temperature, however, the hard constituent formed from the solid solution is deformed only with difficulty and the strained condition produced is relieved only slowly. Hence, hot working below the lower critical temperature is not economical except on very thin material because of the high requirement for deformation and the excessive wear on the shaping equipment.

When steels containing more than 0.87 per cent carbon are cooled from high temperatures, precipitation of a very hard and brittle constituent, called "cementite," begins at the line *HJ* of Fig. 1-VIII and continues until the steel cools to its critical temperature (1333°F.). If the steel is allowed to cool undisturbed from this temperature, the cementite forms in the boundaries of the grains of the austenite, causing brittleness due to the brittle nature of the cementite constituent. On the other hand, if hot working is continued through this range, the cementite is made to form in very small, rounded areas in the grains themselves and has much less effect upon the steel as a whole. For this reason, the hot working of high carbon steel is carried down to the lower critical temperature.

In general, then, the lower critical temperature is the lower limit of hot working for steel, regardless of carbon content. It should be remembered that the presence of alloying elements affects the temperature at which all these transformations take place and must be taken into account among other factors, in determining the proper finishing temperature for an alloy steel. If the temperature at which hot work is started is so adjusted that the piece will be finally shaped when it reaches its lower critical temperature, it will have the minimum grain size obtainable by hot working and still be in an unstrained condition. If large pieces are heavily worked at temperatures below this

point, there is danger that internal cracks will be formed which ruin the part.

There is one further point to be taken up in this connection. When a piece of metal is being deformed by hot working while it is cooling, neither the upper nor the lower critical transformations occur at the temperatures indicated by the lines in Fig. 1-VIII, but occur at lower temperatures depending upon the amount of work done and the rate of cooling. The greater the amount of work and the faster the rate of cooling, the more these transformations are depressed for any given steel of a certain size and shape. For our purpose here, mechanical work can be thought of as depressing the transformations by interfering in a mechanical way with the formation of the new constituents. For this reason, the hot working of some parts, particularly of small section and low carbon content, can be carried somewhat below the lower limit of hot working as indicated in Fig. 1-VIII, before the steel transforms and increasing power requirements for further deformation become excessive.

In rolling mill or forging practice, the foregoing rule in regard to finishing temperature is not strictly adhered to for several reasons. For parts of large size, the finishing temperature cannot be too low because the power requirement for deformation becomes excessive and the metal is too rigid to flow or work readily. The same is true of parts to be formed into intricate shapes as a considerable degree of plasticity is required in these cases. Another factor of primary importance is the required tonnage output. The operating schedules of many plants require that the metal be deformed as rapidly as possible to the desired final shape and size in order to produce a definite tonnage per day. In many cases, the desired physical properties and final grain size can be obtained by subsequent heat-treatment, and great care need not be taken with regard to the finishing temperature. In other cases, particularly certain classes of alloy steels, the finishing temperature must be carefully controlled in order to obtain the desired properties.

It was brought out in the preceding chapter that any one crystal in the ingot contains segregated areas by virtue of its manner of solidification. The crystal skeleton and hence the crystal center are richer in iron than the parts near the outer edges of the crystal. Mechanical working does not entirely eliminate this segregated

condition (nor does diffusion), and these segregated areas are elongated in the direction of flow or working of the metal. Treatment of a longitudinal section of a hot-worked piece with a strong acid shows up this effect as laminations or lines running in the direction in which hot work was carried out.

The physical properties of the fabricated part, particularly resistance to shock and ductility, are usually greater when measured in the direction of these flow lines than in a direction perpendicular to them. In other words, the physical properties are usually better in the direction of hot working. In cases where the finished article is to be subjected to rather severe stresses in a certain direction, the part should be so fabricated that the direction of greatest working coincides with the direction of greatest stress.

Hot work may be used to obtain the final desired size and shape of the piece, or it may be used as a preliminary operation and the final size and shape obtained by cold working. Hot working, of course, is the preliminary forming method in all cases and, if the specifications for dimensions and surface finish of the completed articles are not too rigid or the desired physical properties not too high, the parts also are finished by this method. Owing to the fact that steel contracts upon cooling from hot-working temperatures and usually warps somewhat, other finishing methods are often necessary in order to obtain small tolerances on dimensions.

Cold Work.—Cold work is done at atmospheric temperature. The working of the metal heats it up by internal friction in the metal itself, but it readily cools between deformations. Since hot fabrication precedes cold-working operations, the metal usually comes to this stage with a rather fine and uniform grain size. It is, therefore, strengthened considerably and will stand much more cold deformation without rupture than if coarse-grained material were processed by this method.

Steel is comparatively rigid and unyielding at atmospheric temperature and the effect of cold work on the metal is considerably different from the effect of hot work. The steel itself has a much different internal structure at room temperature than it has at hot-working temperatures. Instead of being composed of austenite or of austenite and ferrite, steel containing less than 0.87 per cent carbon at room temperature is made up of ferrite

and a hard constituent, referred to above, called "pearlite." The amount of pearlite increases with carbon content and makes the cold working of high carbon steel a difficult operation. The reasons for the presence of these constituents will be found in Vol. III of this series, where they form an important part of the study of ferrous metallography.

When steel is subjected to cold work, the grains of both constituents are crushed and broken up into a much larger number of small fragments, the extent of the crushing and the depth of its penetration depending upon the amount of cold work. At atmospheric temperature, however, the mobility of the atoms is so low that the metal cannot recover from this strained condition by the formation of new grains as it can at hot-working temperatures. Cold work also serves to elongate both constituents in the direction of working.

The effect of cold working on the steel as a whole is greatly to increase its strength and hardness and as greatly to decrease its ductility. Each succeeding deformation hardens the metal still more until the metal either refuses to be deformed further at the pressure used or cracks under excessive pressure.

In order to relieve this strained condition, it is necessary to heat the steel to a temperature where the mobility of the atoms is great enough to allow the crushed fragments to reform as small unstrained and equiaxed grains. This can be partly accomplished at 1100°F. (about 600°C.) where the crushed ferrite grains are rapidly converted into small unstrained ones, but the pearlite grains are unaffected by this treatment, remaining in their elongated and distorted form. This treatment, called a "process anneal," lowers the strength and softens low carbon steel enough to allow a considerable amount of further cold deformation. Since high carbon steels contain a large proportion of pearlite which is unaffected by the process anneal, a different treatment is necessary to bring about the necessary ductility for subsequent cold work. Several treatments are used depending upon the results desired. These treatments are patent annealing, spheroidize annealing, and normalizing to produce large grain size, all of which will be described in a later section. Since high carbon steel is normally much harder than low carbon steel, extensive cold working is usually carried out only on low carbon steel and particularly upon rimmed steel.

As the cold-working process is usually carried out on low carbon steel, the hot-worked, semifinished piece is treated in an acid solution (pickled) to remove the scale and give the surface a clean bright finish. It is then deformed an amount consistent with the particular steel's capacity to undergo cold work, given a process anneal, and cooled to room temperature. Either the annealing is done in an atmosphere that will prevent scaling or the metal is pickled to remove the scale formed. This procedure is repeated, if necessary, until the piece is just slightly larger than the final size desired and the article then given what is called a "finish" anneal (also called "true" or "full" anneal). This anneal is carried out by heating the part just above its upper critical temperature, holding it there for a short period, and cooling it back to atmospheric temperature. At the annealing temperature the steel is entirely converted to austenite which is present at hot-working temperature, all strain is removed, and very small grains of the solid solution are obtained. On cooling to room temperatures, the steel changes back to the two constituents referred to above but without any distortion of the grains and, if the anneal is properly carried out, with a very fine grain size. The steel is then pickled if necessary and deformed cold to the final dimensions. Since this finishing treatment hardens and strengthens the metal again, the amount of this final deformation depends upon the properties desired in the finished article.

It is interesting to postulate why steel is not cold-worked at temperatures above atmospheric temperature in order to decrease the power required. The reason for this is that when steel is worked in a range of temperature from about 400 to 750°F. (about 200 to 400°C.), it rapidly becomes very brittle and is almost impossible to work at all. This temperature range is called the "blue brittle range," because in this range steel assumes a blue color on its surface when heated in air, owing to its oxide film. This range of temperature is avoided in cold working operations. The metal can be worked just under the lower critical temperature but it is not often done as better control of grain size and dimensions can be obtained by working at atmospheric temperature.

Comparison of Hot and Cold Work.—Cold working produces greater strength, greater hardness, a more accurate finish as to dimensions, and a better surface, both as to luster and grain size

than any method of hot working. Cold working is used as a finishing operation, therefore, when any or all of these qualities are desired in the finished product. Sheet, strip, and wire products are examples of this class of work.

Hot working is always used to shape the ingot roughly to the desired size and shape and it may be used to finish the piece. In this case, the articles often have to be straightened cold as hot-worked articles warp more or less in cooling from the finishing temperature. Whereas hot working increases the strength and ductility of the steel over its properties in the cast state, it does not have such a profound effect on the strength as does cold work. Hot-working methods are used to finish many large articles, of which I beams, large angles, and pressure-welded pipe are typical examples.

The differences in the effects of hot and cold work on the crystalline structure of the steel depend upon the difference in the degree of mobility of the atoms in the metal and the malleability of the metal itself at the temperatures used. In both cases, the mechanism of crystal deformation is the same, but at hot-working temperatures the metal is able to recover from the strained condition (owing to its great atomic mobility) while at atmospheric temperature it cannot. This accounts for the permanent hardening effect of cold work. Small articles can often be cold-worked to produce a given set of physical properties more easily and uniformly than by any heat-treatment method.

Suggested Questions for Study and Class Discussion

1. What factors require study in deciding whether to cast or mechanically shape a certain steel part?

2. Discuss the structural changes occurring in steel at various temperatures that affect fabricating operations.

3. What is the general effect of grain size on the properties of the finished steel? How may it be controlled during fabrication?

4. Why is cold work never a preliminary fabricating operation?

5. Compare the effects of hot and cold work on steel.

CHAPTER IX

GENERAL METHODS OF FABRICATION

Methods of Hot Shaping.—There are three methods of hot-working steel: *hammering*, *pressing*, and *rolling*. All these methods are in use at the present time, but by far most of the steel ingot production is fabricated by rolling. Hammering and pressing are classed together as forging methods although the actions of the two are entirely different. We say, therefore, that steel is forged or rolled, depending upon which general method of fabrication is used.

Hammer Forging.—Hammering is the oldest known method of working metals and was originally done with a hammer wielded by the workman. The first power hammer, built in England, was run by water power and consisted essentially of a heavy hammer head on the end of a beam lever. A cam arrangement raised the hammer and allowed it to fall of its own weight on the anvil or bottom die. This type of hammer, called the "tilt hammer," had two serious disadvantages. The first of these was that the upper and lower dies (the hammer and anvil) were parallel in only one position since the hammer described the arc of a circle in falling. The second was that the blow of the hammer was least when most needed, *i.e.*, when working large pieces. Since the magnitude of the blow of the hammer was dependent upon its weight and the distance through which it fell, the larger the piece being forged, the shorter the drop of the hammer and the smaller the blow that was exerted.

With the advent of steam power, it was soon utilized to furnish power for the hammer. The first, built in 1842, utilized steam to raise the hammer vertically above the lower die by having the hammer connected to the lower end of a vertical steam piston. The first disadvantage of the old tilt hammer was overcome as the two dies were kept parallel at all times, but the second still remained since the hammer was allowed to fall freely. The double-acting steam hammer was invented in 1888 to overcome

the second disadvantage by driving the hammer downward by steam as well as raising it.

The modern double-acting steam hammer is shown in Fig. 1-IX. The lower die, or anvil, is supported on a heavy foundation to absorb the shock of the blow. A heavy frame, equipped with guides for the hammer and placed over the anvil, supports the large steam cylinder at the top of the structure. The frame is supported on a foundation independent from that of the anvil.

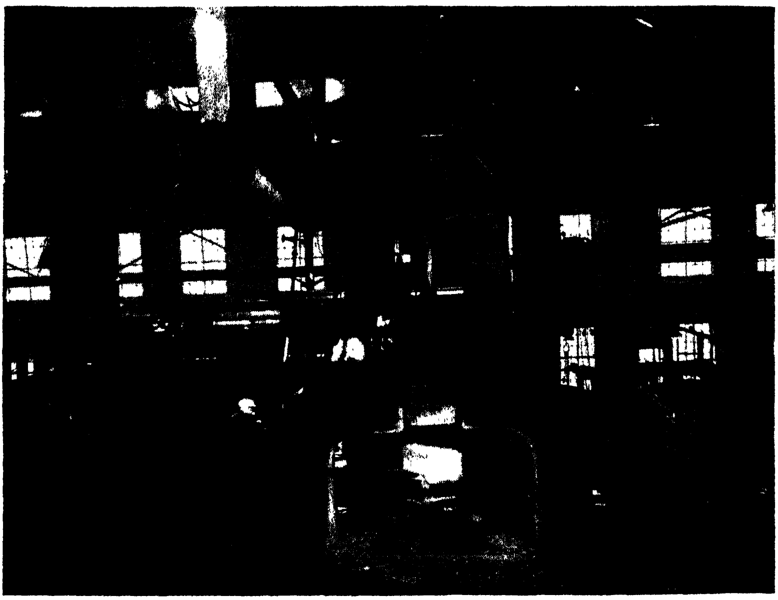


FIG. 1-IX.—Double-acting steam hammer in operation. (*Courtesy of the Bethlehem Steel Corp.*)

This is necessary because the shock of the blow would soon throw the frame out of alignment if it were placed on the same foundation as the anvil. The hammer is fastened to the lower end of the piston rod and travels up and down between the guides as steam is admitted alternately to the lower and the upper sides of the piston. The force of the blow is regulated by controlling the steam admitted on the downward stroke and in this way is made practically independent of the length of the stroke. The sizes of forging hammers vary, the size usually being based upon the heaviest blow that the hammer is capable of delivering. The

estimated equivalent of this blow in tons of weight is the size of the hammer. The sizes in use today vary from a few tons to about 50 tons, depending upon the size of the piece of steel being forged. Sizes much larger than this have been built but the shock of the blow from a 100- or a 150-ton hammer was so great that other machines in the plant were thrown out of alignment. The advent of the forging press for heavy work displaced these very large hammers.

The dies are usually made from alloy steel, forged to shape, machined, and carefully heat-treated. The dies must be quite massive to withstand the shock of the blows and hence must be very carefully prepared and made from the best steel obtainable for the purpose. The design, manufacture, and heat-treatment of these large dies is a difficult job and is usually undertaken only by experts in that line. The upper face of the anvil and the lower face of the hammer are often cut so that simple shapes may be forged such as round, square, and hexagonal pieces. In order to finish a piece by the hammer, several sets of dies are often needed, each set being of smaller size and perhaps of different shape.

Many articles, such as machinery parts and certain tools, are made under the hammer by a process known as "drop-forging." The upper and lower dies are cut in such a way that the cavity formed when they are placed face to face represents the desired final size and shape of the article. A piece of hot metal is then forged between these dies by repeated blows until it is squeezed into and completely fills the cavity between the dies. If more intricate shapes are being drop-forged, two or more impressions in the dies are needed in order to shape the piece.

When a piece of steel at the correct forging temperature is subjected to a blow, a large pressure is exerted upon a relatively small area for only an instant and then removed. The working of the metal is mainly in a direction perpendicular to the faces of the dies, although some of the force of the blow is transmitted in the metal in a direction parallel to the dies. Owing to the shortness of the time during which the metal is subjected to the pressure, the metal recovers somewhat from the blow and the penetration of the working into the metal is not very deep because the pressure is released before the metal in the center of the part being forged has sufficient time to yield. Furthermore, the

amount of yield is not great in proportion to the force of the blow, and it takes more pressure to accomplish a given result than would be the case if the application were slower. The localizing effect which the hammer produces causes the metal near the surface to be thoroughly worked. This results in a very fine grain size in this portion of the forged part. Moderate blows of the hammer, if continued long enough, will gradually consolidate the more or less porous center of the piece.

Excessively heavy blows, however, have a tendency actually to open a cavity in the center of the piece if the part being forged is large. This is due to the fact that very heavy blows elongate the surface metal and set up stresses in the coarser interior which tend to pull it apart. An actual cavity is opened only when a large piece is forged fairly cold with heavy blows, but minute defects can be formed by this action at normal forging temperatures with too heavy blows. The forged part has a very fine grain size at and near the surface if correctly worked, but unless the piece is thin or a great amount of work is done upon it, the center will be coarse and relatively unaffected with regard to grain size. The metal is compressed in the direction of the blow and usually elongated in the direction of the major axis of the forging.

The resistance of the metal to deformation under shock, together with the intermittent action of the hammer, makes this method of hot working a slow one. The expert forger, however, can control the process within very close limits and in this way produce parts of excellent physical properties if they are thin enough for the hammer to work them thoroughly. The finishing temperature and the force of the blow applied at different stages of forging and at different temperatures are particularly under the control of the operator.

The foregoing reasons account for the superiority of some hammered materials over parts fabricated by rolling methods. Drop-forged parts are superior to castings because of the mechanical work done on them. In order that drop-forgings may be made economically, however, it is necessary that a large number of parts be made in order to pay for the expensive dies used. Castings are often cheaper under any conditions, but the forgings are sometimes preferred because of their better properties.

The hammer-forging process is usually carried out by first reducing the cross section of the ingot by forging and then cutting this section into convenient lengths for further processing. The smaller lengths are reheated to the desired temperature and then forged to the final size and shape.

Press Forging.—The forging press has displaced the hammer for heavy work such as armor plate and naval guns because it overcomes the two great disadvantages of the hammer: the loss of efficiency due to the instantaneous nature of the blow and the superficial working due to the same cause. These are overcome by a very slow application of pressure.

The first forging press was built in England in 1861 and introduced into this country about 1887. The modern press is shown in Fig. 2-IX. It consists essentially of a hydraulic cylinder supported on two pairs of heavy steel columns which are anchored to a single base casting of great weight and strength. The ram of the hydraulic cylinder is vertical, the upper forging die is fastened to the lower end of the ram, and the vertical columns act as guides for the ram and die. The lower die rests face upward on the heavy base casting that supports the cylinder. The entire machine is securely anchored to a massive foundation. When some fluid is forced under pressure into the cylinder at the top, the ram carrying the upper die is forced down on the piece to be forged which rests upon the stationary lower die. The pressure exerted by the die can be readily controlled by manipulating the pressure of the fluid entering the hydraulic cylinder. The pressure is usually applied to the metal slowly and is gradually increased to a maximum which may be maintained until the metal yields. The press is equipped with small auxiliary hydraulic cylinders which lift the ram back up to its starting position.

Forging presses vary quite widely in size, depending upon the work they are designed to accomplish. The size of the press is usually designated as the maximum pressure in tons which the press is capable of delivering. Presses in use today vary between about 3,000 and 15,000 tons capacity, the larger sizes predominating. Since much of the work done by presses is of too large a size to be handled by the workmen, large forgings are held on the lower die by an overhead crane and turned by moving the chains supporting the forging. The dies used on the forge press

are similar to those used on the hammer, except that greater use is made of V-shaped dies on the press.

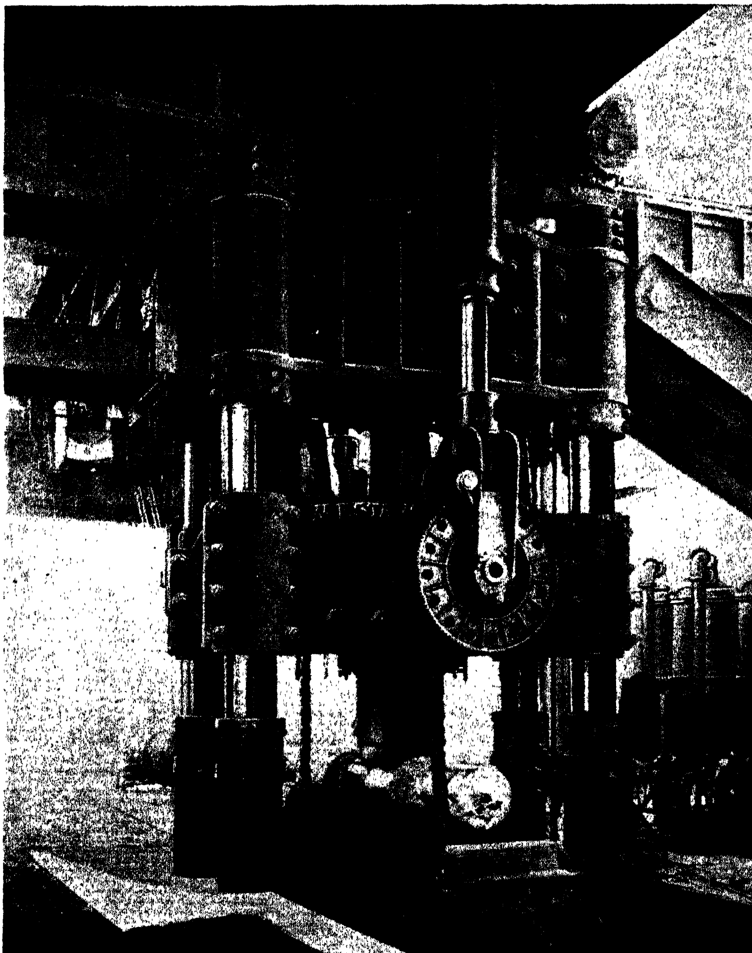


FIG. 2-IX.—Fourteen-thousand-ton steam hydraulic forging press. (*Courtesy of The Mesta Machine Co.*)

The effect of press forging upon steel is entirely different from that of hammer forging. The slow application of pressure by the press produces a kneading action in the metal and causes the effect of working to penetrate deeply into the metal. The

grain refinement and consolidation of the porous center of the ingot can be very effectively carried out by proper manipulation of press-forging operations. The ingot can be entirely reduced by the press through the use of the proper dies, or the ingot reduced partly by rolling and then forged. The forging press is used for shaping large articles in which soundness and superior properties are required, such as naval armament, armor plate, and cracking vessels for oil refineries. More intricate dies can be used to shape many articles by press forging, large wheels being a fairly common example. Several sets of dies are often required to accomplish the desired result.

In comparing the press with the hammer, several advantages of the press are important. The first is the increased beneficial effect on the metal. Also, the absence of shock in the press is of advantage both in the handling of the forgings and in the construction of the machine. A greater proportion of the power put into the press is utilized in deforming the metal than is the case with the hammer because so much of the hammer blow is absorbed by the resilience of the anvil and by the earth. The cost of working material under the press is less than with the hammer because the press shapes the metal faster than the hammer, fewer men and less skilled labor are needed, and the fuel consumption per ton of output is less. On the other hand, the impact of the hammer is advantageous in some respects. The impact knocks the scale off the metal while in press operations trouble is sometimes experienced from scale being pressed into the surface of the metal.

It should be remembered, however, that each of these methods has its applications and its proper place in the general scheme of fabrication. Hard and fast rules as to when each should be used cannot be given because of the wide variety of articles that are being fabricated daily and because of the overlapping of the application of each method. In general, however, the press is used for heavy work requiring good physical properties while the hammer is used on forgings of smaller section where surface refinement is of paramount importance, and on drop-forging work.

Rolling.—Owing to the rapidity with which fabrication can be carried out by rolling and the high efficiency of the process compared to other methods, rolling has come to be the principal

fabricating method. This method has expanded greatly since its beginning in 1783, because of the wider variety of sections now being produced by it and better design of rolls and rolling mill equipment, particularly auxiliary equipment for handling the material between passes through the rolls.

It was early found that by cutting appropriate grooves in the rolls, and feeding the bar of steel into these grooves, shapes could be produced by rolling. One-half of the desired shape was cut in the upper roll and the other half in the bottom roll and directly below it. Such a groove is called a "pass." If one pass was not

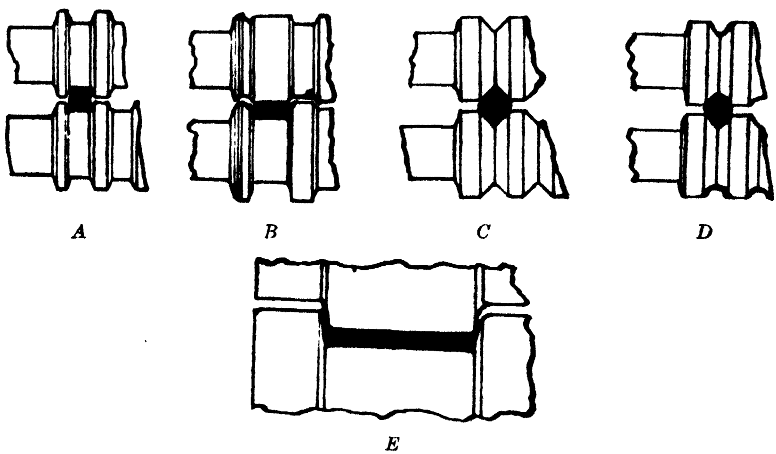


FIG. 3-IX.—Typical passes in rolls.

sufficient to form the material and several passes through this groove would not shape the piece, several sets of grooves of varying size and shape were cut in the rolls so that by feeding the bar into each of the grooves in turn, the steel could finally be shaped to the desired degree. With the exception of plate, sheet, and strip mills, practically all rolls are grooved in some manner at the present time.

Several different types of passes have been developed. The ones shown in Fig. 3-IX have been found to be the most efficient in reducing the section in semifinishing and "roughing" mills—the preliminary rolling mills. Of course, many different types of passes are in use in finishing mills where the shape of the desired section is obtained. *A*, *C*, and *D* are called "open passes" while *B* and *E* are closed passes. In open passes half of the

section is cut in each roll while in a closed pass the piece is buried entirely in one of the rolls so that three sides are closed in one groove and the fourth by the *tongue* or *former* on the other roll. A variation of this type for wider material (sheet bar) is shown in *E* and is called a *tongue-and-groove* pass. Passes *A* and *B* are called *open* and *closed box* passes, respectively. *C* is a *diamond* pass and *D* is called a *Gothic* pass.

The rolling mills in use today are very complicated pieces of machinery and no two of them are exactly alike, even for the same type of work. Mills for different types of work vary widely in size, in design of the rolls themselves, and in mechanical details, owing to the wide variety of articles fabricated by rolling. For these reasons, a description of the principal types of rolling mills will be taken up in a separate chapter and only a very brief summary will be attempted here.

The first mechanical working of the ingot is done on a large and powerful mill called a *bloomer* or a "*blooming mill*" (known as a "cogging mill" in England). The blooming mill receives the hot ingot from the soaking pit and reduces it to a smaller size—"breaks it down"—and the piece issuing from the mill is known as a bloom. The bloom is a semifinished product, usually square or rectangular in cross section, which is subsequently rolled on a billet mill, finishing mills, or used for forgings. Most blooming mills consist of two rolls mounted one above the other, the direction of rotation of which can be reversed in order that the metal can be passed back and forth between the rolls. Grooves are cut in the rolls of appropriate size and shape to accommodate the ingot and the various reductions. The distance between the rolls is adjustable and the rolls are slightly corrugated in order to grip the piece with greater ease. This type of blooming mill is called a "two-high reversing bloomer."

For rolling smaller sizes of semifinished pieces, *billet mills* are used. These mills are smaller than bloomers and are of two main types. One type, called a "three-high" billet mill, consists of three rolls placed in a row in a vertical plane. Each roll rotates in a direction opposite to the roll next to it. In this way the metal can be fed between the center and bottom roll and then back between the center and top roll. The other type, called a "continuous" billet mill, consists of a series of two-high pairs of rolls set in a line so that the metal passes continuously

from one pair to the next, only one reduction being carried out by each pair of rolls. The billets coming from the billet mills are then rolled on finishing mills of widely varying descriptions. Bars, small I beams, angles, and a variety of other products are finished in this way.

In comparing rolling and forging, it should be remembered that each method has its own field of usefulness. In the first place, many articles are so intricate in shape that rolling is impossible and they must be shaped by forging methods. Also, extremely large pieces must be worked under the press as they are too difficult to handle with rolls and the working of the metal would not be sufficiently thorough. Besides, rolls large enough to accommodate such large sizes would not be economical. Owing to the high speeds at which rolls operate, the tonnage output is much greater than with forging and the cost correspondingly lower. This high-speed operation, however, lessens the control that the operator has over the process and usually results in a lower quality of product from rolling. By slow rolling speeds and careful control of draft and finishing temperature, rolled products can be made practically equal in quality to well-forged parts. To obtain this, however, the greatest advantage of rolling over forging—that of large production at low cost—is sacrificed. In usual rolling mill operation, the finishing temperature is generally too high for the best quality of product since the operator usually desires to obtain the maximum tonnage at the lowest power requirement. The hammer and the press, because of slower operation, are both under better control than rolls but are more expensive to operate for the same reason. Articles are forged, therefore, when physical properties are the primary requirements and cost of fabrication is secondary. Hence, great care is usually taken in forging work.

Rolls.—The manufacture of rolls demands a considerable amount of care, skill, and experience in foundry technique. Rolls must be strong enough to resist the pressure applied to them, ductile enough to withstand the shock produced as the piece enters the pass, hard enough to resist rapid wear, and sound enough so that surface defects will not develop and spoil the surface of the work as it is rolled. When the design and composition of the roll are being developed, all these factors must be considered so that the roll will suit the purpose for which it was intended.

Following this, the melting technique, alloy content, molding methods, and heat-treatments are developed to meet the particular requirements.

The several grades of roll castings produced and the service to which they are best adapted, based on experience, are as follows:[1]

1. Plain carbon steels. For blooming mill, structural shape mill, roughing, breakdown stand in hot sheet mill, etc. Generally chosen only for economical considerations such as small-lot rollings.

2. Alloy steels—0.50 to 1.25 per cent carbon. For blooming and slabbing mills, roughing stand in rail mills, roughing stand in structural shape mills, sheet jobbing mills, etc. The chosen range depends upon the characteristics of the mill and the weight of section rolled.

3. Alloy steels—1.40 to 2.75 per cent carbon. For billet roughing, intermediate stand of rail mills, intermediate and finishing rolls in shape mills, continuous mill rolls for billets, sheet bar, skelp; merchant mill strand and finishing rolls, etc.

4. Alloy iron. Gray iron for intermediate and finishing stands of structural shape mills, continuous mill and merchant mill finishing, strip mills, rod mills, etc.

Chilled iron for tin and sheet hot and cold mill rolls, sheet bar billet and skelp finishing stands, rod mills, plate and strip mills.

Of the above grades, probably the one having the widest application is the so-called semisteel containing 1.40 to 2.75 per cent carbon. The use of this grade is extending and is now finding application even in the roughing stands of many mills. This wider use is due to the fact that following ordinary annealing treatment, the hardness is quite stable at operating temperatures.

Methods of Cold Working.—Cold working is a finishing operation and the articles coming to this stage of fabrication have been refined in structure and roughly shaped by hot work. The general methods by which cold shaping is carried out are cold-rolling, cold-pressing, and cold-drawing.

Cold Rolling.—Cold rolling is usually carried out on sheet for various purposes. It may be desired to remove the curves and kinks produced by handling and hot rolling, to produce a smooth and polished surface, or to adjust the strength and hardness of the

[1] BENT, Q., Modern Rolling-mill Practice in America, *J. Iron Steel Inst.*, **138**, No. II (1938).

sheet in addition to producing the desired final dimensions. If the hot-rolled sheet is pickled and then cold-rolled, a hard, dense, and smooth surface can be imparted to it. If the sheet is specially treated before rolling, the cold-rolled sheet can be produced with a highly polished surface which is somewhat more resistant to atmospheric corrosion than would ordinarily be the case. As each pass through the rolls increases the strength and hardness of the material at the expense of ductility, practically any desired strength and hardness can be obtained within the limits of the full annealed and drastically cold-worked state by proper control of the extent of cold work and annealing.

Rolls for carrying out cold-rolling operations must be very strong, hard, and smooth in order to do the work required of them. The amount of reduction in thickness accomplished at each pass is small because of the hardening of the metal and the power required. The details of cold rolling will be taken up in Chap. XII of this book.

Cold Pressing.—Plate for various purposes is often shaped between dies by means of a heavy hydraulic press. A wide variety of articles can be formed with great rapidity and economy in this way. Often, several sets of dies are necessary in order to shape the part completely. Bolsters, braces, and plates for steel railroad car construction are formed from plate by this process, which is commonly known as "flanging." No appreciable reduction in thickness is effected by cold pressing, the part being merely formed to shape by this process. Except when the material is bent, the amount of cold work done is relatively small.

Cold-drawing.—The process of drawing steel through dies is used principally in making wire and in finishing seamless steel tubing. In both cases the principle of operation is the same. The metal is pulled forcibly through a die having an aperture which is smaller in size than the part entering it. This causes a reduction in the cross section of the piece being drawn and a corresponding increase in its length. The operation obviously cold-works the metal and necessitates frequent annealing if much reduction in cross section is to be accomplished.

In drawing wire, the reel of wire is mounted behind the draw-plate containing the die, pulled through the die, and rolled on another reel. Rotation of this reel furnishes the power by which the wire is drawn through the hole in the die. For coarse

sizes, the dies are usually of hard, high carbon or alloy steel, carefully machined to size and very smoothly finished. For very fine sizes and where extreme accuracy as to size is required, tungsten carbide or diamond dies are used. Chilled cast-iron dies are used for the intermediate sizes of work.

The wire-drawing process is capable of elongating and reducing the cross section more than any other shaping method and of maintaining at the same time a high degree of accuracy as to size and shape. If the bearing surface of the die is correctly finished, the surface of the drawn wire can be made exceptionally smooth. By regulating the amount of cold work after the last annealing treatment, wire of the same composition can be made to develop a wide range of physical properties.

Sizes of seamless steel tubing, up to 12 in., I.D., are frequently cold-drawn to the final size. In this way, thinner walls can be produced than by hot rolling, smaller diameter tubing can be made, a better surface finish can be obtained, the physical properties can be more easily controlled, and the dimensions of the cold-drawn tube are more accurate. In drawing, the tube is pulled through the ring-shaped die which is smaller in diameter than the entering tube. A mandrel is centered in the opening to maintain the desired internal size and shape of the tube. The pulling process elongates the tube and decreases its thickness and diameter.

Miscellaneous Operations.—An enormous tonnage of steel is shaped by cold stamping and punch press operations. Such a wide variety of shapes is formed by these methods that an adequate discussion cannot be given here. Special dies are used to trim the "blank," shape the piece, and punch holes, if necessary. The machines used vary so widely in size, design, and method of operation that a general description is impossible. An outstanding example of stamping is the manufacture of automobile bodies and fenders from thin sheet stock. The sheet is usually heat-treated, blanked, trimmed, and formed to shape between the dies of several presses.

Suggested Questions for Study and Class Discussion

1. Compare hammer forging with press forging from the standpoint of the effect on the metal.
2. Compare rolling and forging in general.
3. Describe the different kinds of rolls and the methods of making them.
4. For what purpose is cold rolling used?
5. For what purposes is cold drawing used?

CHAPTER X

GENERAL FACTORS AFFECTING ROLLING OPERATIONS

Prior to the study of actual rolling operations, it is essential that we study some of the principles of the regulation of the flow of metal between rolls. The effects and kinds of flow encountered in rolling of larger sections such as the ingot and semifinished products will be studied in some detail. Flow as encountered in smaller sections will not be stressed, but in a general way the principles will apply to them as well. All the rolling schemes, however, have as a common aim rapid reduction of area and

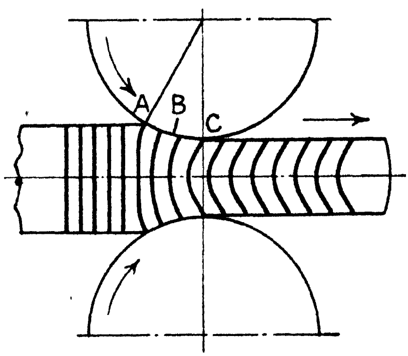


FIG. 1-X.—Diagrammatic theory of rolling.

maximum elongation, or the quickest evolution from blank to shape, consistent with the kind of material being worked.

The process of shaping steel by rolling consists essentially of passing the material between two rolls revolving at the same speed but in opposite directions and so spaced that the distance between them is somewhat less than the height of the section entering them. Very little is actually known of what occurs between the roll face and the rolled material. The common theory, however, may be evolved by studying Fig. 1-X which shows a bar being rolled between a pair of plain rolls. The moving roll faces have gripped and imparted a forward motion to the bar and have in the process effected a reduction in cross-sectional

area and an elongation. The bar is entering the rolls at a rate slower than the delivery speed and has a delivery speed which is faster than the roll surface speed. Between the points A and B the metal is being pulled downward and forward; while between B and C it is being pulled or forced forward much as if it were being squirted from between the rolls. The B point has been chosen arbitrarily as the neutral point between these two actions.

There are a number of variables to be considered when studying such phases of rolling action. First of all, consideration should be given to conditions limiting the amount of draft that can be taken. The mill operator is limited in this case by the power of his drive as well as the grind and slip resulting if the rolls will not bite. Referring again to Fig. 1-X, it is generally considered that the angle A to C should not be greater than 30 deg. or the total draft taken without ragging of the rolls should not be more than 10 per cent of the roll diameter. Greater angularity of bite without slippage may be effected by employing some extraneous means of pushing the material into the rolls, by ragging of the rolls, or the result of the power of the delivery push, as in a continuous mill, which enables the successive stands to take heavier bites.

Variable effects are also brought about by the nature and kind of material undergoing rolling. It is found that Bessemer and open-hearth steels will react with different effects under the same mill conditions. Bessemer analyses are found to promote more slippage when hot than is encountered with open-hearth steel. If we attempt to obtain a given reduction, using plain rolls, which is easily taken with open-hearth grades, on a Bessemer grade of the same carbon content, there will be a characteristic slippage at the roll surface. Rolls for these grades are either ragged or roughened to pull it through. The ragging marks thus produced on the Bessemer grades will roll out and not appear on the finished bar, but open-hearth grades rolled on such ragged rolls will show the marks on the finished bar unless the ragging is carefully done and well rounded.

The temperature of rolling is of importance because of the widely varying flow encountered when rolling relatively hot and cold steel in the same pass and roll setting. The size of the rolls and their speeds will have a marked influence. The greater the roll diameters the greater is the draft that can be taken without

exceeding the limiting angle of rolling. For a given draft, however, the area of metal in contact with the rolls increases with the roll diameters and thus increases the power required for rolling.

The greater the speed of rolling the more the effect on the metal tends to approach the superficial effect of hammering, *i.e.*, the greater the stretching effect and the less the actual work of compression. The best quality of rolled steel is produced by slow rolling speeds where the effect on the metal tends to approach the kneading action of the forging press. At high rolling speeds, defects caused by tears increase as the rolls begin to slip on the metal. The large increase in power required and the strain on the rolling equipment at high speeds usually limit the speed of rolling to a value where the steel is not injured. The smaller the size of section being produced the more rapidly the rolls must be run because small sections cool quickly and must be finished before they become too cold.

The kind of roll material, the physical condition of the roll faces or grooves, and the amounts as well as the method of applying cooling water will bring about noticeable variations.

The rolling effect of a bar in which a series of pins has been placed prior to heating and rolling has been shown in Fig. 1-X. The cross section of the bar shows that the particles nearest the roll face and in contact with it are bent or affected considerably more than the material inside. The surface zones are forced between the rolls at a much greater rate of speed than the core material. The core material is not only being pulled along with the surface material but is also setting up a considerable counteracting force to the forward motion of the surface zones, because it remains anchored to the unrolled end of the bar. By this action of the elongation and spread of certain zones to the exclusion of others the entire section is worked. The more or less static interior sections, by reacting against the force of rolling, work the material just as definitely as do those forces which are tending to elongate directly. It is by these means that the working of steel between rolls brings about increased tensile strength, increased density through the closing of internal cavities, and, to some extent, increased ductility as compared to cast metal.

From the previous studies of ingot structures it is known that because of the freezing characteristics the ingot is quite weak

physically. On account of these conditions the surface is particularly susceptible to rupture into surface cracks and hence must be worked lightly in the first passes employed in the reduction. With properly applied work on all sides of the ingot this skin arrangement is rearranged into a structure that runs parallel to the surface and direction of rolling. The surface metal now is more plastic and malleable and is strong enough to resist surface cracking under the subsequent heavier passes.

The subsequent work on the horizontal faces of the large thick mass of metal tends to elongate the surface zones and has little

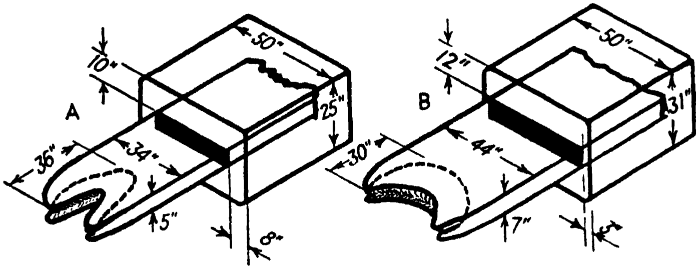


FIG. 2-X.—(*Courtesy of Louis Moses.*)

if any effect on the core. The vertical sides during this action show disturbance by the breaking of the scale. Some movement, greatest near the rolls and little or none at the center, can be observed.

In the rolling of various products, arrangements are made to select the size and weight of ingots to suit the given conditions. This is not always applied completely as certain economic and practical considerations and in some cases metallurgical limitations prevent it. Mold sizes, therefore, have become more or less standardized to meet the major line of products. The best practice is to apply as nearly equal work to all sides of the semi-finished product as is possible. This results then in using square ingots for the rolling of square blooms and oblong ingots in a number of sizes in rolling slabs.

Let us consider the effect of the rolling of two differently dimensioned slab ingots which were cast with straight and flat bottoms (Fig. 2-X). The crop ends of the differently sized slabs as they were rolled show the resultant flow by the lengths of the horns of the fishtail. The horns, produced with a 16-in.

total width reduction at A, are longer than those produced with 6-in. width reduction at B. The resultant flow in rolling can be seen to be greatest at the edges with lessened similar effects at the center line and interior of the slab. The fishtail ends were formed in the early stages of the rolling when the partly reduced ingot was still a large mass. The resultant work on the large mass has tended, as has previously been described, to elongate the surface. Similar rolling pressure exerted on thinner sections would penetrate the interior and produce rounded instead of overlapping edges.

In Fig. 3-X there is shown the form of an ingot butt as made in a specially shaped stool along with the resultant slab crop.

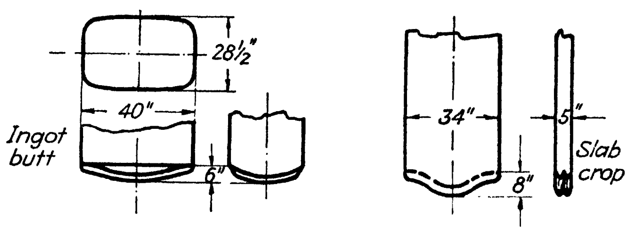


FIG. 3-X.—(*Courtesy of Louis Moses.*)

The swell in this case has prevented the formation of the fishtails and end overlaps by initially supplying enough metal at the proper point to fill the portions that otherwise would be vacant.

In some particular applications ingots are cast with beveled corners with the subsequent rolling arranged so that these beveled corners are maintained and worked upon by the rolls. The purpose in this procedure is to avoid overlaps.

Thus far we have been studying rolling action from the viewpoint of elongation. It is also essential that we consider what is occurring to the cross section of the material. Let us study this characteristic by considering Fig. 4-X, which shows sectional views of partly rolled ingots. A represents a section of about 20 in. square which has been broken down from a larger ingot. With ordinary grades of steel, rolling of this section to a thickness of 12 in. may be permitted without turning it. Beyond this, however, a concave condition will develop at the edges. The differential effect of roll pressure between edge and center resulting in an edge spread can be seen in A. If the rolling were continued in the same direction until the thickness

of the piece became about 6 in., there would result a very definite overlap or creased edge, as shown at *B*. These edges would cool to a lower temperature than the body of the mass and would thus have a different rate of elongation. This would in all probability produce saw-toothed cracking.

The section is turned up and given an edging pass as at *C* to prevent this cracking and obtain a uniform structure at the edges as well as in the main portion. With the edge thus squared, rolling from a 12-in. section would produce a convex or swelled

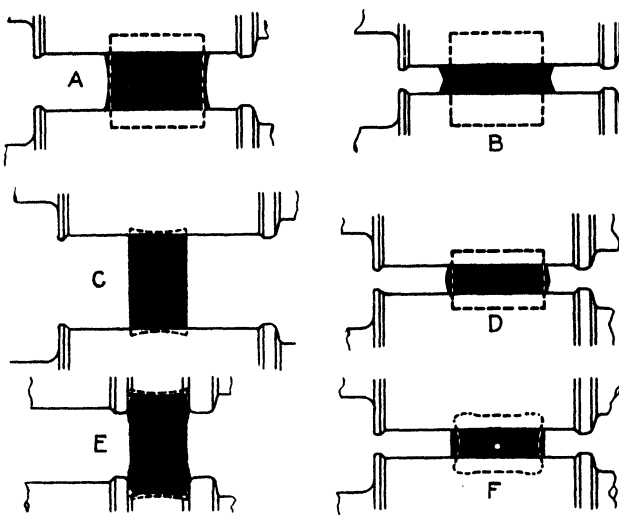


FIG. 4-X.—(*Courtesy of Louis Moses.*)

edge as at *D*. This is caused by the penetration of the rolling pressures into the core. The relative thinness of the section and the fact that the core would by this time be the hottest part and hence somewhat softer than the surface have caused this response to the applied pressures. Since it is difficult to hold such a section in a vertical position as at *C*, a grooved pass is usually provided as at *E*, the walls holding the section in the desired position without tipping. Advantage is also taken with this pass, of introducing a convex surface at the bottom of the grooves so that in later reductions a straight-sided edge will be produced as at *F*.

In this series of reductions we have seen that the metal flow consists of two components, elongation and spread, with the greatest effect being produced through elongation. Spread may

be explained as being due to the section attempting to escape in the direction of least resistance to flow. Within the limits of the total width, spread will occur at every point across the section with the increments being greater at the edges than at the middle. In Fig. 5-X we have shown a section of the width of a bar (to a very much exaggerated scale) divided into ten ordinates, five on each side of the center line, which is being subjected to the rolling pressure. Spreading is opposed by this friction between the rolls and the bar.

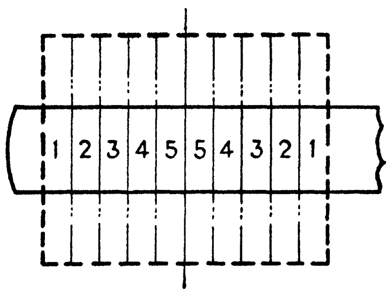


FIG. 5-X.

The extreme section 1 may be assumed to spread freely, but the next section 2 in spreading is obliged to move the preceding section 1 against the opposing friction and hence will spread less. This effect continues until we reach section 5 at the center line which must overcome the resistance caused by all the sections between it and the edges. The total amount of spread is therefore the summation of the spread of all the sections.

This explains the reason for the rounded crop ends which are generally observed on rolling such a section. This has resulted from the fact that with unequal spread there will be unequal elongation. In this case there will be minimum spread with maximum elongation at the center sections with maximum spread and minimum elongation at the edges.

In general it has been found that spread will occur with such rolling of bars up to widths of 16 in. Little variation in gauge is encountered on bars from this figure up to 24 in. wide. When rolling wide stock as in plate mills, however, it is found that the centers of the stock will be somewhat heavier than the edges. This condition has been generally attributed to roll deflection and roll wear, but the part they play in causing this

condition is limited. The part played by roll deflection is in general taken care of by turning the rolls so that they have a larger diameter at the center than at the ends.

Roll diameters also have a definite relation to spread and elongation. Small-diameter rolls will produce considerable elongation with a minimum amount of spread, while under the same conditions large-diameter rolls produce relatively more spread and less elongation. This phase is a particularly important principle in the use of relatively small rolls in continuous wide strip mills.

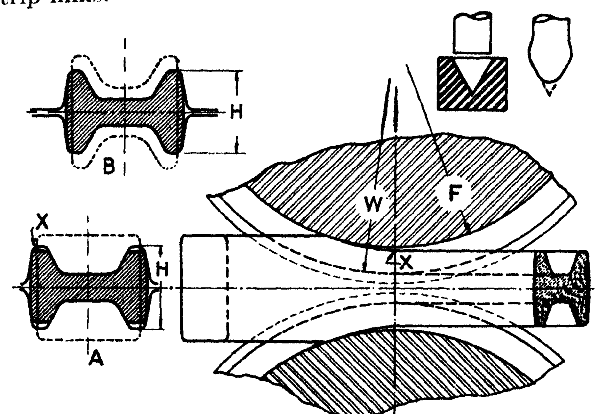


FIG. 6-X.—(*Courtesy of Louis Moses.*)

Discounting roll wear and roll deflection, the explanation of this gauge variation may be made by considering the effect of giving a wide plate a single pass. Following the draft it will be found that the front end is straight, the back end will tend to be concave, and the middle will gauge heavier than the edges. The center apparently has rolled ahead of the edges because it cannot spread and hence must elongate. The edges try to keep up the center. There is perhaps some opportunity for the edges to spread a very little and thus be reduced in thickness. In addition, however, the theory has been advanced that "a drawing action occurs which draws the metal at the edge zones into the direction of the greatest pull of the middle zone elongation and causes the reduction of edge thickness."

Several illustrations of other kinds of rolling will be shown to illustrate further the effects of spread and elongation. The lay-

outs in Fig. 6-X, which will serve to illustrate an important aspect of flow encountered in some kinds of shape rolling, is elementary and does not represent practical groove construction. In working a thin web from a rectangular bloom there is always a loss of flange height. The cross section in the figure shows that this is due to the fact that the longer diameter W which works on the web has a higher peripheral speed than the diameter F at the flange edge. The larger diameter, therefore, pushes the

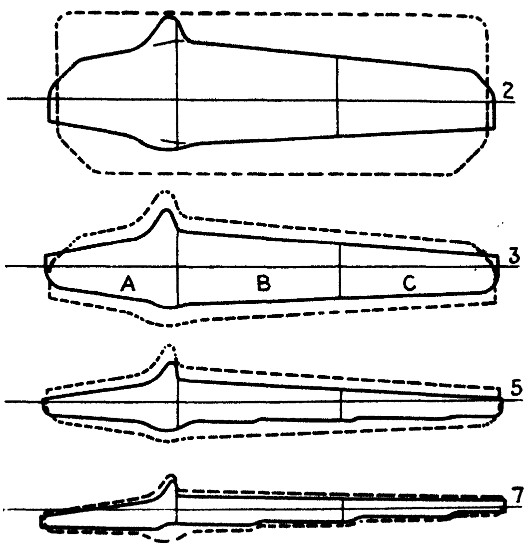


FIG. 7-X.—(*Courtesy of Louis Moses.*)

metal of the web forward at a faster rate than the metal at the flanges and hence will drag the metal from the flanges. The result then, as is shown at X, is that the material does not touch the roll at diameter F.

In rolling operations where a previously formed blank is used, allowance is made by keeping the flange height high enough in relation to the web thickness to allow for this loss. This is illustrated in B of the figure where the flange height H is such as to compensate for the elongation of the web.

Another kind of flow is encountered which is the exact reverse of spreading. Figure 7-X shows four grooves in outlines as used in the rolling of a tapered tie plate. With the intervening grooves not shown, these are selected to illustrate the principle involved.

Here the drafting from pass to pass is arranged so that the amount of work is proportionally equal at all the various thicknesses. As subdivided and lettered at pass 3 for convenience, the parts *A*, *B*, and *C* each receive the same percentage of area reduction. This results in heavier measured drafts at the thicker parts and lighter drafting, by scale measurement, at the thinner ends.

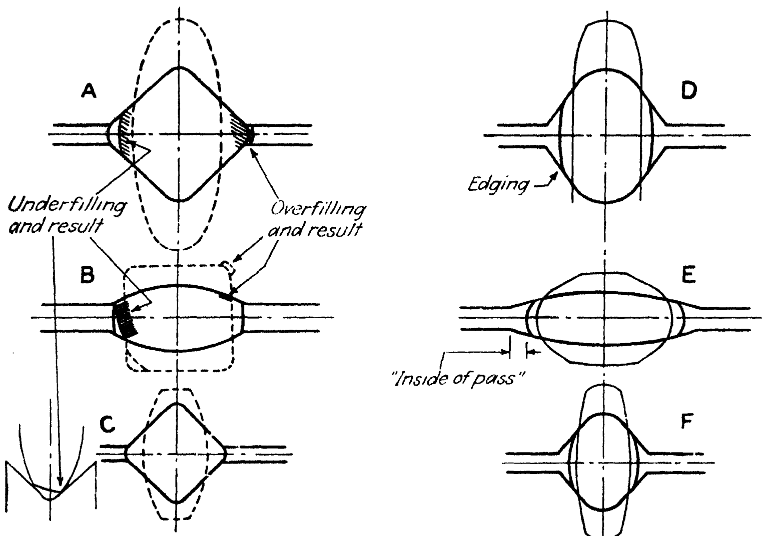


FIG. 8-X.—The use of square passes creates hazards which, in tonnage production, require the utmost care in preventing overfills and underfills. The pass design in *A*, *B*, and *C* has a number of thick pointed ovals which tend to pinch the metal into the apex of the pass. In addition, this difficulty is aggravated by the lack of end symmetry. In pass design *D*, *E*, and *F*, the thick ends of the ovals enter well into forming passes and upset but do not cause pinching. (*Courtesy of Louis Moses.*)

If the drafting were otherwise arranged and work, as measured in fractional inches, applied equally to all the parts across the face of the section, the percentage of reduction at such respective parts would vary. In such a manner a ¼-in. reduction would perhaps occur to the thin ends and also to the thick middle causing the percentage of reduction to be greatest at the ends. The thinner parts of this type of section invariably will travel along the often mentioned path of least resistance and flow to the thick center of the bar. Note that the opposing faces of the two rolls form a wedge-shaped opening. With such kind of groove construction there would be nothing to induce the metal to flow into

the curtailed end dimensions. As stated, the inclination is for it to flow in the opposite direction, or into the thick parts and then into elongation.

By arranging the work as described and as illustrated, a resistance is set up to such inward flow and counterbalances it. The ends of the rolled section are thus maintained at their appointed places and over-all widths produced to the desired dimensions. This type of pass construction counteracts, to some extent, the temperature variations across the section because the thin ends cool more rapidly than the thick centers.

Various schemes of rolling, as for example those employed in rod mills, depend upon ways of bringing about maximum elongation to the bar being rolled. Some typical open passes are shown in Fig. 8-X. In pass *A* an oval is entering a breakdown square. The equivalent square is then turned and enters an open oval as at *B*. These two passes are always considered in pairs. *C* is a continuation of the breakdown in which the oval is turned and entered into an open square.

The "oval-square" passes, used as process or breaking down passes, require careful designing and roll adjustment, particularly in continuous mills. The ovals must be well pointed to enter and fill the apex of succeeding squares. Bluntly pointed ovals tend to cause a pinch at the apex of the square pass. A square bar entering a succeeding oval must be produced so that its diagonal measurements across the corners are closely equal to each other as otherwise a malformed termination of the oval will result. Maintenance of these features requires that the bar must completely fill the pass. This is a difficult matter, especially when rolling quality bars, because an accurate control of volume throughout the bar length frequently overfills the tightly filled passes and damaged fins result. The results of underfilling and overfilling are also shown in *A*, *B*, and *C*.

"Oval edging" or "oval round" grooves are employed to overcome these difficulties. The bar in these works "inside the pass." In other words, it is never so dangerously close to the roll collars as to cause a fin, even though in stock control, area manipulations are made by roll settings. The more or less bluntly formed ovals enter the generously rounded bottoms of edging passes and upset, but do not cause a pinching action. These features are illustrated in *D*, *E*, and *F*.

The flow characteristics taking place when a square bar enters an oval pass need some elaboration. It is found that the elongation at the edges will be relatively greater than in the center because of the greater reduction of area at that section. The edges, however, are held back by the center and in an effort to

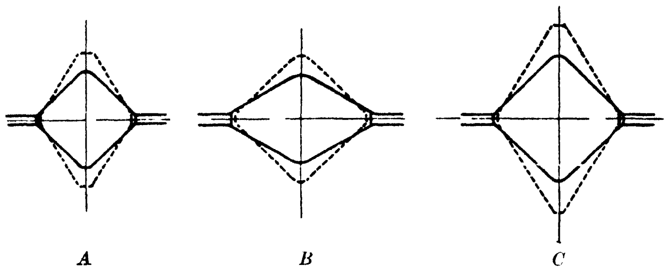


FIG. 9-X.—(*Courtesy of Louis Moses.*)

follow the path of least resistance will have a strong tendency to spread. This tendency to spread is retarded by the arched walls of the oval groove and will, therefore, tend to flow the metal into the thickest part and add to the flow of metal in elongation.

A similar action takes place when an oval section enters either a square or round pass. The elongation is quite large and the total spread small.

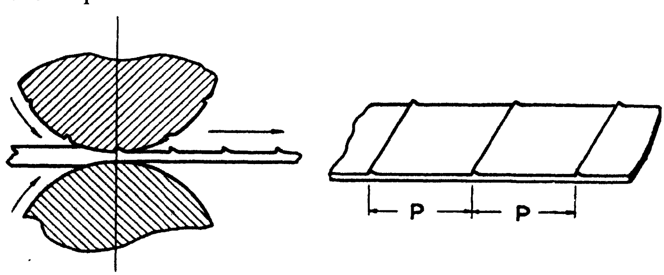


FIG. 10-X.—(*Courtesy of Louis Moses.*)

Passes *A*, *B*, and *C* of Fig. 9-X show a breakdown scheme for rolling billets, where the same principle is employed to maintain the corners.

The effect of temperature variations on rolling a bar may be shown by Fig. 10-X, which shows a shouldered tie plate with transverse lugs formed in one finishing pass. The sketch shows the general shape of the section with the desired length *P* between the lugs. However, on rolling a length of 70 ft. the variations of *P* from end to end were as follows:

Back				Front
←70 ft.→				
←1/5→	←1/5→	←1/5→	←1/5→	←1/5→
−0.109″	−0.083″	−0.002	+0.001	+0.172

The plus amount in the front as compared to the minus amount in the back was due to temperature variation. A difference in temperature of 50 deg. will produce this effect. This is due to the hotter front end lending itself more readily to the flow in the forward direction than does the colder back end.

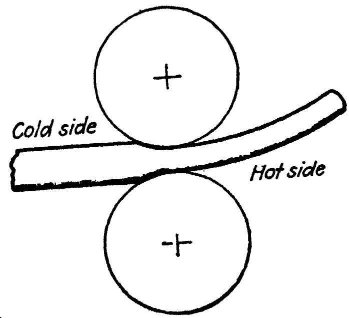


FIG. 11-X.—(*Courtesy of Louis Moses.*)

Another effect of temperature variation is shown in Fig. 11-X in which the shaded portion, as shown in the rolling position, is the hottest. The hottest part, as in the case of the tie plate, lends itself more readily to the flow between the rolls than does the colder side. The bar then bends at a long radius on the hot side and short radius on the cold side. A similar effect is produced in a flat section which has one of its edges hot and the other cold. The result in this case would be a horizontal bending.

Suggested Questions for Study and Class Discussion

1. Discuss the effect of temperature on the flow of metal in one of the typical passes discussed.

2. If a bloom was being rolled between plain rolls, would the spread be uniform throughout the entire length of the section?

3. Discuss, in general, the relation between angularity of bite and slippage and the limiting factors in the reduction of sections in the flat rolling of steel.

4. Would friction caused by rolling make the temperature of the piece higher than immediately before?

5. In what ways would you think the metallurgical department could be of service to the rolling departments?

6. If you were to study the resultant flow of the metal in a given mill, how would you proceed in gathering the basic data?

7. In general, what effects are produced in the rolling operation?

8. If you were rolling plates what type of ingot would you use? Why? What procedure would you use in rolling from ingot to finish plate? Why?

CHAPTER XI

ROLLING MILL PRACTICE

The methods used in fabricating shapes by rolling are so many and varied, as to both details of operation and equipment used, that only the barest outline can be attempted here. No one plant is equipped to produce even a majority of the products that are made by rolling, and no two plants use exactly the same procedure in shaping identical articles. By the same token, two rolling mills in different plants and producing the same article are rarely, if ever, identical in construction and operation. It is obviously impossible, therefore, to attempt anything like a complete discussion of fabrication. It was thought best to attempt a general survey of the methods used and then illustrate the principles involved by typical examples of actual mills and methods of operation.

Several mill terms require definition. The ingot is first rolled on the blooming mill. The product of this mill is called a *bloom*. Since reduction of the larger cross-sectional dimension beyond 6 in. is seldom done in this mill, semifinished products 6 in. in their greater cross-sectional dimension or larger are usually known as blooms. Reduction is further carried out on a billet mill in most cases, the product of this mill being known as *billets*. Since billet mills are rarely constructed to reduce the bloom to a smaller thickness than 1¾ in., semifinished products between this size and 6 in. are usually called billets. The limiting sizes given above for blooms and billets do not hold strictly, however, owing to varying practice in some plants. Semifinished material larger than 6 in. in the larger cross-sectional dimension is sometimes known as a billet, but the above limits hold fairly well in most cases. Blooms are usually square or rectangular in cross section but, if semifinished material is desired, the width of which is much greater than the thickness, the reduction is carried out on a slabbing mill and the product is called a *slab*. In mill operation, when the ingot is reduced to a suitable cross section on the blooming mill, it is sometimes too long to handle conveniently and is cut

into several blooms, the number depending upon the size of the ingot, the cross section of the blooms, and the use to which the bloom is to be put. The same is true of billets and slabs.

The hot mills that roll the wide variety of shapes directly from ingots, blooms, or billets are classified in Table 1-XI. These mills are by no means the only ones used, as many different types of mills are required to roll the products of the semi-finishing mills indicated.

Rolling mills may also be classified according to the number of rolls contained in the roll housing: *two-high, three-high,* and *four-high mills.* In three-high mills, each roll rotates continuously in one direction only, while in two-high mills, provision is sometimes made for reversing the direction of rotation of the rolls at will, and the mill is called a *reversing mill.* In four-high mills, the four rolls are set vertically one above the other and the two inner rolls can be made to rotate in a single direction or can be made reversing. Each outer roll in contact with an inner roll always revolves in a direction opposite to the inner roll in contact with it. Four-high mills are used for the hot rolling of sheet and the cold rolling of sheet and strip.

As might be expected, the highly efficient and complicated rolling mills of today have all been developed from a two-high mill with smooth rolls rotating in a fixed direction and powered by a water wheel. If the piece being rolled required more than one pass through the mill, the man, called the catcher, who caught the piece with a pair of tongs as it emerged from the rolls returned it to the roller by placing the piece on top of the upper roll, the rotation of which carried the piece over the mill to the member of the crew on the other side of the mill. This man, called the roller, grasped the piece with his tongs and fed it through the rolls again. A modernized form of this mill, called the "pull-over mill," but still of the same simple type, is used today in rolling sheet and tin plate and will be described more fully later in the text.

With the advent of steam power for rolling mills, it was possible to reverse the direction of rotation of the rolls so that the material could be passed back and forth between the rolls. Further developments introduced powered rolls set in a roll table to handle the material between passes and start it back through the rolls again, thus dispensing with the catcher. Manip-

TABLE 1-XI.—CLASSIFICATION OF MILLS*

I. Mills rolling materials from ingots:
  A. Semifinishing mills
    1. Blooming (cogging) mills
    2. Slabbing mills
  B. Finishing
    1. Universal plate mills
II. Mills rolling materials from blooms:
  A. Semifinishing
    1. Billet mills
    2. Sheet bar mills
    3. Skelp mills
  B. Finishing
    1. Structural shape mills
    2. Rail mills
    3. Wheel mills
    4. Wheel and circular shape mills
III. Mills rolling materials from slabs:
  A. Semifinishing
    1. Hot rolled strip
  B. Finishing
    1. Plate mills
      a. Sheared plate
      b. Universal mill plate
      c. Hot rolled strip
IV. Mills rolling materials from billets:
  A. Semifinishing
    1. Rod mills
    2. Piercing mills (for tubes)
  B. Finishing
    1. Shape mills
    2. Bar mills
    3. Band mills
    4. Hoop mills
    5. Merchant mills
      a. Guide mills
      b. Bar mills
V. Mills rolling materials from hot rolled strip and all finishing:
  A. Hot rolling sheet mills
  B. Cold reducing mills
    1. Sheet
    2. Strip

* From CAMP and FRANCIS, "The Making, Shaping, and Treating of Steel," 5th ed., 2d impression, The Carnegie-Illinois Steel Corp., 1940, p. 669.

ulators were later added to turn the ingot and bloom between passes. This became increasingly necessary as the size of ingots increased to where they were too heavy for man power to handle. These auxiliary devices as well as the mills themselves have been further improved by the application of electric power.

The act of passing the steel being rolled back over the top of the upper roll of the pull-over mill in order to be given another pass, undoubtedly conveyed the original idea for the three-high mill. By placing a third roll above the upper roll of the two-high mill, twice the number of passes could be made in about the same time and with the same amount of handling. For three-high mills designed to roll heavy material, tilting or lifting roll tables were supplied to raise the piece being rolled to the upper passes of the mill.

With other advancements in rolling mill practice came the *continuous mill.* As greater efficiency and tonnage became a requisite, larger and larger semifinished material was used to produce rods and other finished stock in longer lengths. This increase in billet size increased the number of passes necessary to shape the finished articles to a point where they could not all be put on a single stand of rolls. The use of several stands of rolls to produce a certain piece resulted in the development of many different types of mills, one of the most important being the continuous mill. In this type of mill, several stands of two-high rolls are arranged in tandem in such a way that the material being rolled passes through the stands of rolls in a straight line. Since the reduction in cross section accomplished by each pass elongates the piece being rolled, each stand must be driven faster than the preceding one in order to take up the slack. In the case of thin material, such as strip or skelp (strip destined to be formed into welded pipe or tube), the slack is sometimes taken care of between certain passes by a mechanical contrivance that forces the excess material to loop down into a pit provided between the stands. In this way, excessive rolling speeds on the finishing stand are avoided.

A *merchant mill* may be defined as any small mill that regularly produces more than one shape. This definition covers a very large field and many types of mills fall in this class. Most small sections such as rounds, squares, and small angles are rolled on merchant mills. These mills are sometimes made up of a two-high

reversing or a three-high roughing stand for reducing the cross section of the billet and a separate train of rolls, usually set with their rolls in line and driven from a single engine. The finishing train is usually composed of both two-high and three-high stands and the necessary grooves cut in these rolls so that, by using appropriate passes, several different sections may be shaped on the same mill. In most cases a continuous roughing set of several stands of rolls is used.

Several subdivisions of merchant mills may be made. It was early found that longer lengths of small sections could be rolled by supporting the metal with steel guides as it entered the various passes. This was first done on rounds because it was discovered that a round could be rolled from an oval in one pass if the oval were of the correct dimensions and properly supported with its long axis vertical on entering the pass. This led to the use of an oval guide on the entering side of the pass. The guide is of slightly larger size than the oval bar entering the pass and supports it in the desired position. It was later found that other sections could be shaped more conveniently with the use of guides, and mills employing guides came to be known as *guide mills*.

As the billet length was increased, owing to increased tonnage demands, the capacity of the finishing train was cut down because of the necessity of allowing the bar to be rolled through one pass completely before it could be transferred to the next pass and started back through it. To overcome this, the practice was begun of starting the bar through the next pass before it had completely emerged from the preceding one, thus forming a loop. This was done on all passes in the finishing train, and the elongation of the rod extended the size of the loop in each succeeding pass. The looping was done by the catchers who grasped the end of the bar as it emerged from the pass, pulled it around, and inserted it in the next pass. Mills where this practice is used are called *Belgian* or *looping mills*. This practice was later improved by providing looping tubes or troughs called *repeaters*, to guide the bar from one pass to another and thus dispense with the catcher.

Where the section being rolled is not suitable for looping, the *cross-country mill* is sometimes used. This type of mill is made up of several stands of rolls, arranged in trains or trains

and tandem sets. The operation is semiautomatic in most cases and no men are required on the mill floor, as live roll tables, transfer mechanisms, etc., turn the bar and reverse its direction several times in passing through the different stands of the mill. A *combination mill* is one in which the roughing passes are made in a continuous mill and the finishing passes on a looping train.

In addition to the mills indicated above, there are many others used for particular purposes. For example, *rail mills* for rolling railroad rails; *structurals mill* for rolling I beams, channels, etc.; the *Schoen mill* for rolling car wheels; the *Mannesmann* and *Stiefel mills* for piercing seamless tube; *Diescher elongator* for rolling light-walled tubes and wall thicknesses as light as 0.06 in.; and the *Steckel mill* for cold-rolling strip. The *universal mill* is one which, in addition to horizontal rolls (usually two-high), is provided with vertical rolls that roll the edges of the material being processed. Some of these mills will be described later in greater detail.

We can now turn our attention to more or less detailed descriptions of several typical mills and their auxiliaries. Since no two mills are exactly alike as to details of construction, only the general features will be given. The attempt has been made to select typical examples for description and those which are of comparatively recent design and, therefore, contain the up-to-date features of the modern mills. Rolling mills are very expensive pieces of equipment, and steel plants rarely remove them from service merely because some innovation in design or construction has been found to be better in some other plant. For this reason, many of the older plants are still using mills of an old type right beside new equipment of the very latest design. As long as the old mills will do the work required of them, it is not economical to scrap them in favor of more up-to-date equipment. This accounts, in part, for the continued use of old types of mills.

Blooming Mill.—Three different types of blooming mills are in use at the present time: two-high reversing, three-high, and continuous bloomers. Of these, the *continuous blooming mill* consists of several two-high stands of rolls (usually four or five) arranged in tandem so that the path of the ingot lies in a straight line and only one pass is made in each stand of rolls. Each stand is usually driven by an individual electric motor. This type of mill has

the advantages of a very high tonnage output and great sturdiness of the two-high stands. It is much more expensive to build and install than the other types of bloomers. This mill has the added disadvantage of being able to roll only one size of bloom from one size of ingot without changing the rolls, and only a limited number of passes are available in any case. The features of the construction and operation of the continuous mill will be evident from the description of the continuous billet mill to be

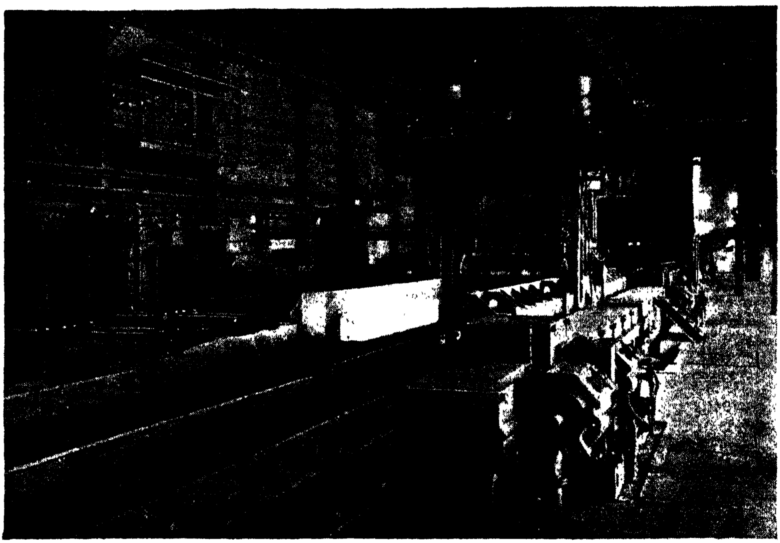


FIG. 1-XI.—Two-high reversing blooming mill. (*Courtesy of The Mesta Machine Co.*)

taken up later. In essential features, the continuous bloomer is only a larger edition of the continuous billet mill.

The *two-high reversing blooming mill* is the most generally used type and for that reason will be described in considerable detail. Succeeding descriptions will merely point out differences in construction features.

The reversing blooming mill, shown in Fig. 1-XI, is made up of several parts, namely, the housings and chocks, the adjusting mechanism, the driving mechanism, the rolls themselves, and the auxiliary equipment. The *housings* are very heavy cast-iron or steel frames, designed to support the rolls and adjusting mechanism securely in place, and are spaced the correct distances apart

by means of heavy tie bars. The housings are usually cast in a U form with the top of both housings cast in one piece with the crossbars and the entire top bolted to the housings themselves. The housings are fastened at their bottoms to mill shoes which, in turn, are bolted to a heavy concrete foundation. Arrangement is made for moving the housings on the shoes in order to line up the mill more easily after construction.

The open space in each housing is called a *window*. In these windows are placed the heavy steel, bearing-lined castings, called *chocks*, which support the necks of the rolls. The chocks for the bottom roll contain bronze or babbitt linings to act as bearings and are equipped with adjusting screws so that the bottom roll can be easily lined up in the mill. In recently constructed mills of all types, more and more use is being made of roller bearings to decrease friction losses, to make for smoother operation, and to allow heavier pressures to be used. The chocks for the upper roll are lined also and are connected to the adjusting mechanism, called the "screw-down," by means of which the distance between the rolls can be adjusted. The screw-down is a rather complicated arrangement of gears connected to either a hydraulic cylinder or an electric motor. By operating the screw-down the roller can very rapidly adjust the distance between the rolls to any desired value which is indicated on a large dial placed on top of the mill. The maximum lift of the upper roll is usually at least 30 in.

Most reversing blooming mills are driven by a single steam engine or electric motor. The more recent mills are electrically driven. The lower drawing in Fig. 2-XI shows the usual method of driving the rolls. The motor shaft is connected by means of a short *spindle* and *couplings* to the *pinions*, which are large steel gears of the herringbone type, set in the large housing as shown. By means of the two pinions set one above the other, both of the rolls are powered and made to rotate in opposite directions. The distance from center to center of the pinions is usually taken as the size of the mill, in this case 54 in. (see Fig. 3-XI). This distance is practically the same as the diameters of the rolls and the minimum distance between their centers. Blooming mills in use today are between 32 and 54 in. in size. Some smaller mills, however, are used for rolling special alloy and high carbon ingots of small size. In most

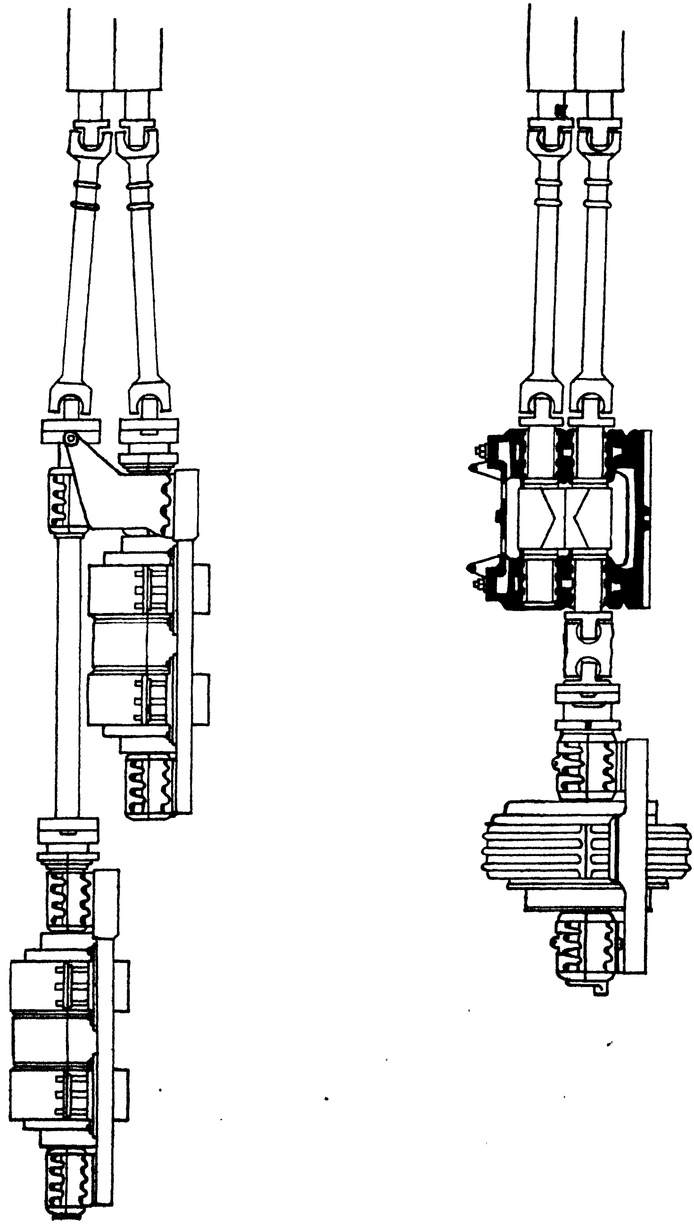


FIG. 2-XI.—Blooming-mill drives. *(From Blast Furnace and Steel Plant.)*

cases, the ingots are small enough to be turned and fed by hand labor.

The pinions must be connected to the rolls by spindles in such a way that the lower roll can be moved slightly and the upper roll a considerable distance in a vertical direction. This accounts for the universal coupling connections between the spindles and the pinions and roll necks which permit power to be transferred to the rolls when the spindles are inclined at an angle. The length of the spindles is determined by the diameters

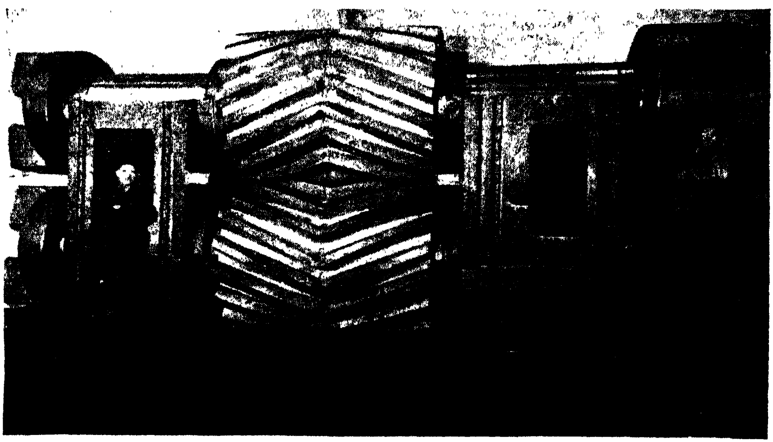


FIG. 3-XI.—A 54-in. two-high pinion stand. (*Courtesy of The United Engineering and Foundry Co.*)

of the rolls and the maximum lift of the upper roll as the transfer of power to the upper roll becomes difficult when the upper spindle is inclined at an angle of more than 10 to 15 deg. to the horizontal. This accounts for the long length of driving spindles on the large mills.

Quite recently, twin motor drives have been installed on several large reversing mills and are being advocated for smaller mills.[1] The method of driving the mill by using this arrangement is shown in Fig. 2-XI. As the name implies, two identical motors are employed, one to drive each roll through appropriate spindles and couplings. The electrical hookup, a discussion of which will be omitted here, is of such a nature that the two motors act as a unit and drive the two rolls at the same speed

[1] WRIGHT and STOKES, *Blast Furnace Steel Plant*, **19**, 980 (July, 1931).

in starting, stopping, reversing, and during rolling. This method of driving eliminates the necessity of the pinions and pinion housing with their accompanying energy losses, maintenance, and repairs. The twin motor drive also allows the use of more total horsepower in driving the mill, thus enlarging the tonnage output by increasing rolling speeds. The mill is smoother in operation, stops, and reverses faster than a mill of the same size equipped with a single-motored pinion drive. As is the case with nearly all modern mills of any type, the motors are placed in a separate room adjacent to the rolls, the spindles extending

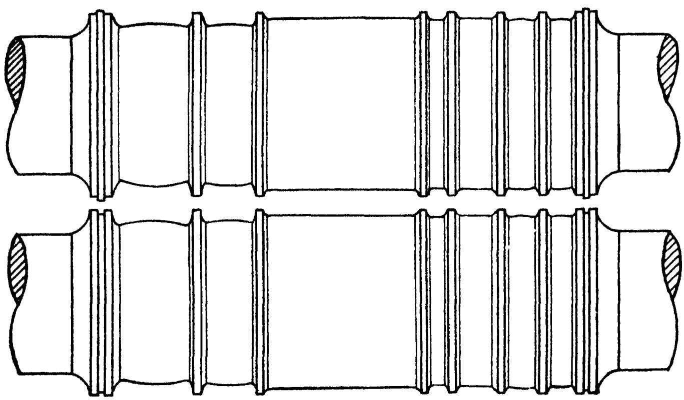


FIG. 4-XI.—A typical pair of rolls for a 40-in. reversing blooming mill.

through the intervening wall. In this way the motors are protected from dust and mill scale.

The rolls for reversing blooming mills are usually of steel of an approximate composition of 0.60 per cent carbon and 0.75 per cent manganese. Figure 4-XI shows a typical pair of rolls for a 40-in. mill. The smaller passes on some blooming mills are sometimes grooved to form beam blanks or other special blanks if the mill regularly produces these types of blanks. All the passes are collared with wide fillets at the bottoms of the collars, the former in order to prevent the metal from spreading too far between the rolls and the fillets in order to keep the corners of the bloom well rounded. The large center pass for initially breaking down the ingot is called the "bull head." The intermediate passes are usually "ragged," *i.e.*, ridged and grooved to a depth of about $\frac{1}{16}$ in. in order for the rolls to grip

the piece to better advantage. The rest of the passes are usually knurled slightly for the same reason. During rolling, the rolls are always cooled by streams of water which are directed upon the top of the upper roll. Because of the fact that the rolls wear away rather rapidly with use, spare sets are always provided. The top of the housing can be unbolted and lifted off with a crane and the rolls replaced in a very short space of time. Worn rolls can be dressed and redressed in a lathe several times before the grooves become so deep that the rolls have to be scrapped.

The auxiliary equipment necessary for the operation of a reversing blooming mill consists of roll tables, a manipulator, and a shear. A *roll table* consists essentially of powered rollers set horizontally and parallel in a substantial framework for the purpose of conveying the metal between passes through the rolls. The axes of the rollers are placed at right angles to the desired direction of travel of the material. Each roller may be individually powered by a small motor, as in a recent installation, or many of them may be driven by a single motor through a train of bevel gears. A rather narrow roll table usually extends from near the soaking pits to the blooming mill while tables of greater width than the bodies of the rolls are provided on each side of the rolls and of sufficient length to accommodate the bloom during rolling. This portion of the table is made reversing, in order to feed the bloom back and forth through the mill.

Owing to the size of present-day ingots, *manipulators* are required to turn the bloom between passes, to transfer it from one pass to another, and to straighten the piece for each pass, if necessary. One is usually placed on each side of the mill. Each manipulator consists of two vertical side guards set at right angles to the axes of the rolls and capable of movement across the roll table. These side guards are supported and actuated as shown in Fig. 1-XI and, in addition, sets of fingers are provided which move in a vertical direction and slide in guides in one of the side guards for the purpose of turning the piece between passes. With the bloom held loosely between the side guards, the fingers rise from below the roll table, engage one edge of the bloom, and lift this edge up until the bloom falls over on its side. Manipulators may be powered by hydrau-

lic cylinders or by electric motors, the latter being used in the more recent types.

The operation of the entire mill is controlled from a pulpit spanning the table on the delivery side of the mill and located several feet above the table and about 20 ft. from the rolls. From this pulpit the roller and his assistant, or assistants, control the speed of the rolls and the reversing mechanism, the

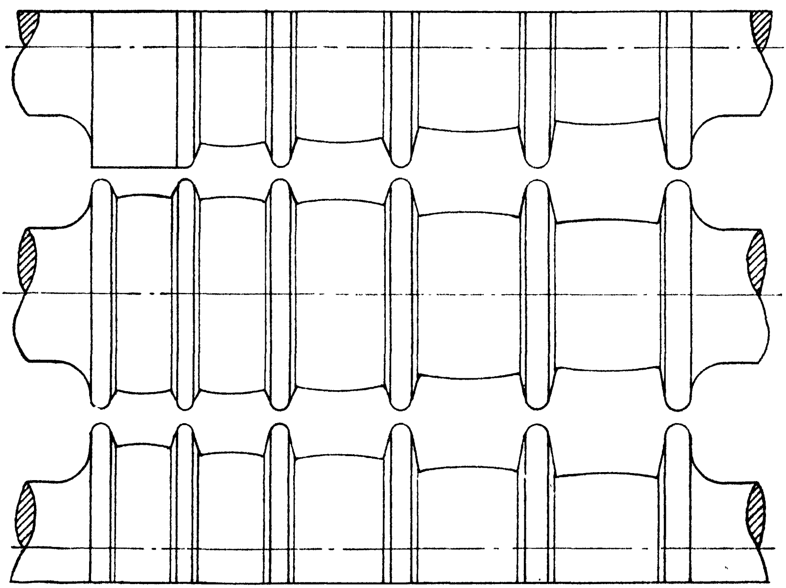


FIG. 5-XI.—A typical set of rolls for a 42-in. three-high blooming mill.

screw-down, the roll tables, and the manipulators. A well-trained crew can carry out the operations with great speed.

The roll table on the delivery side of the mill is extended to the bloom shear, which is a heavy, electrically or hydraulically powered knife, used to crop the pipe and badly segregated portions from the piece and to cut it into several blooms of desirable length, if required.

The *three-high blooming mill* is not used so much as the two-high reversing type but has a wide enough use to merit brief description. The three rolls of this type of mill are arranged one above the other, and passes are cut in them as shown in Fig. 5-XI, which is a typical example of the rolls from a 42-in. mill.

For a mill of the same size as a reversing blooming mill, the rolls of a three-high mill are usually longer in the body to accommodate a greater number of passes, and the rolls are not all of the same diameter. The rolls for this type of mill are much more difficult to design than for a reversing mill because a groove cut

FIG. 6-XI.—A 24-in. three-high blooming mill. (*Courtesy of The United Engineering and Foundry Co.*)

in the center roll to form the upper half of a pass between the center and the bottom rolls must also form the lower half of a pass between the center and the upper roll. Another factor that complicates the design is that in any given pass, the peripheral speed at the base of the groove must be almost exactly the same for both rolls. This fact, together with the different sizes of passes, accounts for the differences in the diameters of the three rolls previously referred to, as the roll diameters must be so

adjusted that the piece emerging from the pass will not curl as would be the case if the peripheral speeds were not the same.

Two types of three-high blooming mills are in use. In one, the middle roll is fixed and the upper and lower rolls have a vertical motion controlled by a motor-driven screw-down mechanism. In the other type, all three rolls are fixed, except for small variations for adjustment. The rolls for the movable type can be made shorter than for the fixed type because several drafts can be made in the first few passes.

Three-high blooming mills are driven by steam engines or electric motors, the latter being more common in recent years. Since the mill runs in one direction only, the motor can be equipped with heavy flywheels which store up energy and smooth out the operation of the mill. The main driving spindle is connected to a three-high pinion stand which distributes the power to the three roll spindles and imparts the same direction of rotation to the top and bottom rolls but a reverse direction to the center roll. Roll tables, which are capable of being elevated to transfer the piece from the lower to the upper passes and back again, must be provided on both sides of the mill. These roll tables are usually electrically operated and a manipulator is provided to transfer the piece from one pass to the next and also to turn it on edge. A photograph of a three-high blooming mill is shown in Fig. 6-XI.

Comparison of Reversing and Three-high Blooming Mills.—The main advantage of the two-high reversing over the three-high blooming mill lies in the greater flexibility of the former, owing to the wide range of the variation of the distance between the rolls. By adjusting the top roll, the mill can roll various sizes of blooms or slabs from ingots of varying size on the same set of rolls. In addition, the drafts in each pass can be varied to suit conditions, such as temperature and composition of the steel. The two-high mill is to be preferred when long lengths of blooms are being rolled because the lifting tables necessary for three-high mills are difficult to design and operate economically if they have to be made unusually long. Again, greater simplicity of the design of two-high rolls and the mill itself is in its favor.

The movable roll type of three-high mill offsets somewhat the greater flexibility of the two-high mill, but the screw-down mechanism for this type of three-high mill is complicated. The

fixed roll type of three-high mill must roll a fixed size of bloom from a fixed size of ingot unless the rolls are removed and a set of different design substituted. A big point in favor of the three-high mill is its much lower operating cost. Much power is lost in stopping and reversing the two-high mill, and the three-high mill can operate at a higher speed, thus increasing its tonnage output. In addition, the large flywheels produce smoother operation and will carry the mill on peak loads. A smaller motor can be used on three-high mills than on reversing bloomers of the same size.

Billet Mills.—Over 50 per cent of the steel produced in the United States is rolled into material of small section and, in order to finish the product without reheating, mills rolling such sections must start with small billets. Many reversing blooming mills are equipped to roll sections 4 by 4 in. in cross section and sometimes smaller but even these sections are too large for some finishing mills. In addition, it is usually uneconomical to tie up the heavy and high-powered blooming mills by rolling small billets on them when a smaller and less expensive mill can accomplish the work to better advantage. Hence the billet mill is used to produce semifinished material from the product of the blooming mills described above.

Almost any mill of medium size may be used for rolling billets as the sections rolled are not of complex shape; the tolerances on dimensions and the specifications as to finish are never very rigid. The main requirements are that they be heavy enough to handle fairly large blooms and rapid enough in operation to reduce the piece to the desired size before it becomes too cold. Two main types of billet mills are used: continuous and three-high mills.

Continuous billet mills vary widely in size, number of stands, and method of reducing the bloom. They all consist, however, of from 8 to 12 stands of two-high rolls, arranged in tandem so that the reduction from bloom to billet is accomplished in a straight line. The rolls are very short, of fairly large diameter, and hence practically unbreakable. The rolls are suitably grooved to reduce the section and, in order to roll a widely different section, a different set of rolls must be substituted.

A continuous billet mill set up to roll either 4- by 4-in. or 2- by 2-in. billets from a 7½-in. square bloom will be described

as a typical example of a continuous mill of this type.[1] This mill consists of six two-high stands with rolls 24 in. in diameter, arranged in tandem, and directly connected to the blooming mill by means of a roll table, and four two-high stands with rolls 18 in. in diameter separated from the other six stands by a roll table and side transfer table. The first six stands are placed rather close together so that the steel is in several stands at

FIG. 7-XI.—A ten-stand continuous billet mill in operation. (*Courtesy of The Youngstown Sheet & Tube Co.*)

once and these stands are equipped with guides between stands to direct the material and twist it through 45 or 90 deg. between certain passes in order to roll the bar on all sides. These six stands are designed to produce a 4- by 4-in. billet from the bloom and, if billets of this size are desired, a transfer tablé pushes the billets off the main roll table and in this way by-passes the four remaining stands of the mill. If 2- by 2-in. billets are desired, the billet from the first set of stands is carried straight on to the four 18-in. stands in which it is further reduced. These four stands are also placed close together and equipped with guards

[1] ANON., *Blast Furnace Steel Plant*, **19**, 1455 (November, 1931).

and guides. The mill is capable of producing 130 gross tons of billets per hour.

The six 24-in. stands are powered by a 5,000-hp. motor and a bevel gear train located in a room adjacent and parallel to the mill. Since the piece is delivered from each pass at a rate faster than that at which it entered, owing to the reduction made, and since the piece is in several passes at once, each succeeding stand must be run faster than the preceding one in order to overcome this lengthening effect. In order to allow for wear in the passes, each stand after the first is run slightly faster than is theoretically necessary, both rolls are made adjustable in each stand, and a slight tension is kept upon the billet. The same arrangement is used in connection with the four 18-in. stands except that these stands are powered by a 4,000-hp. motor.

A flying shear is placed near the beginning of the runout roll table from the mill. This type of shear is synchronized with the delivery speed of the finishing stand of the mill in such a way that during the time it is cutting the emerging billet it is traveling at the same speed as the billet and thus makes a square cut. This type of shear is run either by steam or electric power and, after being set to cut the billet into the required lengths, it will trip automatically at the correct times. A stationary cropping shear is located just ahead of the last four stands to crop the billets if necessary. The runout table delivers the billets to cooling beds placed with their long lengths at right angles to the runout table. Cooling beds are long framework tables built of rails and equipped with chain-driven fingers which take the billets from the runout table after they are automatically stopped and discharged by a device at the end of the runout table. By the time the billets are pushed to the other end of the table, they are cool and comparatively straight, as the cooling table has minimized the warpage.

Two important advantages of the continuous mill are high output and low labor requirements. The metal is rolled down very rapidly, giving it only a short time for oxidation and cooling, while the power requirement is not high. Both long and short blooms can be rolled, which is of advantage as it saves scrap losses at the bloom shear. Equally important disadvantages are the first cost of the mill and the cost of spare rolls, especially when different sections are to be rolled on the same stands.

Also, the time consumed in changing rolls is a disadvantage. The continuous billet mill is particularly adapted, therefore, to rolling large tonnages of one section continuously. For this type of work, this mill is widely used. When new billet mills are installed, they are almost always of this type.

The *three-high billet mill* is constructed much like the three-high blooming mill except that it is smaller in size, the average size of the billet mill being about 28 in. The mill is driven through a three-high pinion stand and short roll spindles and couplings. Either an electric motor or steam engine is connected to the pinion stand and usually to the center pinion. A typical set of rolls for this type of mill is shown in Fig. 8-XI. In these rolls the bloom is reduced to a 4- by 4-in. billet in the seven passes shown in the sketch. The upper and lower rolls are of the same size while the center roll has varying diameters at the bottoms of the grooves. The rolls are usually a little more than 6 ft. long. In mills of this type, guide cages are bolted to the roll housings on both sides of the mill in such a way that guides can be placed both in front of and behind the passes so that the billet will enter and leave the pass correctly.

In order that three-high mills may keep up with rapid production, the operation of these mills must be nearly automatic with regard to manipulation of the piece between passes. Lifting roll tables are usually provided on both sides of the mill and "live" grooved rolls are used in the tables. In one mill of this type, the table that receives the billet from the upper passes is equipped with wide flat collars which correspond to the upper passes in the mill so that the billet is run out on the collars. As the table sinks to the lower passes, stationary fingers project between the rolls and slide the billet off the collars into the line of grooves which correspond with the lower passes. In this way, the act of lowering the table automatically transfers the billet to the next pass. The rolls in the table are then started, the billet sent through the pass, and the piece runs out on a set of grooves in the other roll table. As this table rises to the upper passes, it shifts over the required distance to advance the piece one pass. After the bar is rolled in this pass, the table sinks and shifts back to its original position. Both roll tables are connected and lift and sink together. By this arrangement the manipulation is practically automatic, the roller having to control only

the movement of the roll tables. As many as four billets can be rolled at once in this mill.

Three-high billet mills equipped for automatic manipulation are quite efficient but can roll only one type of section without roll changes. They are also handicapped by the fact that the length of billet that they can produce is limited by the length of the roll tables. Hence, the blooms must be sheared into appropriate lengths in order to be rolled on this type of mill.

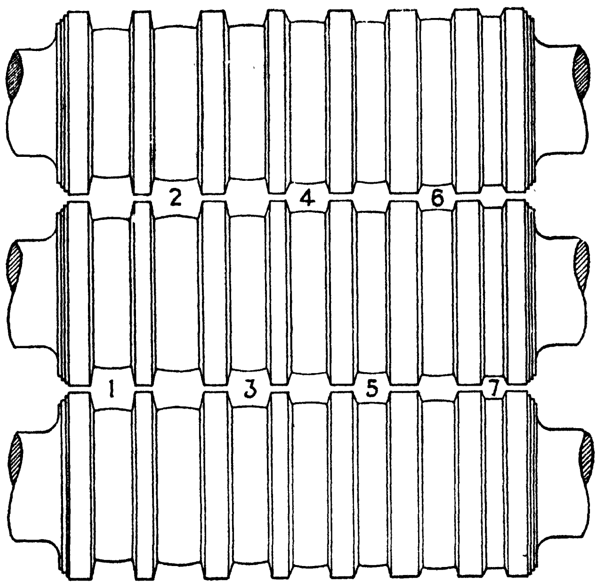


FIG. 8-XI.—A typical set of rolls for a three-high billet mill. (*After Camp and Francis.*)

Shearing nearly always increases the scrap loss at the bloom shear. Many three-high billet mills are in use which are not so nearly automatic in operation as the one described above. In these mills, the operation is much slower and less efficient, tilting roll tables (only the end of the table next to the mill rises, the table being hinged at the far end) are often used, and catchers are employed to turn the billet between passes.

The Rolling of Blooms and Billets.—The layout of this portion of a rolling mill varies widely from plant to plant and depends upon the space available and the type of equipment being used. The operation of such a setup will now be described very briefly.

When the roller in the blooming mill pulpit is ready for an ingot, he blows a whistle to let the soaking pit man know that he is ready to begin rolling. A soaked ingot is removed from the pit by a crane and placed on an electrically operated car, called a chariot (Fig. 9-XI), which conveys it to the approach roll table of the blooming mill. The car is tipped and the ingot dumped on the rollers which are started and the ingot conveyed

FIG. 9-XI.—An ingot chariot bringing an ingot to the blooming mill. (*Courtesy of The Youngstown Sheet & Tube Co.*)

to the rolls. The manipulator squares the ingot away for the first pass through the mill, and the piece is passed back and forth through the rolls until it reaches the desired cross section. The piece is passed back and forth through one groove several times, the screw-down operated after each pass to bring the rolls closer together, the bloom is then turned 90 deg., and the process is repeated. The bloom is then moved to a smaller groove and the procedure carried out as above. Streams of water are played on the top roll to keep the rolls cool and to help blow the scale off the bloom. The number of passes taken on a blooming mill to

reduce the ingot to a bloom is shown in Table 2-XI. Mills are designed to take as much as 20 per cent draft elongation, but in actual practice the draft is held to about 10 per cent. Elongation of the ingot in rolling varies from five to thirteen times, depending upon the area of the finished section.

TABLE 2-XI.*—AVERAGE NUMBER OF PASSES TAKEN ON BLOOMING MILLS TO REDUCE INGOTS TO BLOOMS

Size of blooming mill, in.	Size of ingot, in.	Style	Size of bloom, in.	Number of passes	Elongation
44	28	Round, corrugated	$9\frac{3}{4} \times 9\frac{3}{4}$	25	6.1
44	28	Round, corrugated	$9\frac{3}{4} \times 9\frac{3}{4}$	23	6.1
44	21 × 28	Rectangular	$9\frac{3}{4} \times 9\frac{3}{4}$	21	5.5
44	25 × 30	Rectangular	$9\frac{3}{4} \times 9\frac{3}{4}$	27	7.3
44	23 × 28	Rectangular	$9\frac{3}{4} \times 9\frac{3}{4}$	23	5.9
44	20 × 24	Rectangular	$9\frac{3}{4} \times 9\frac{3}{4}$	21	4.7
44	28	Round, corrugated	9 × 8	25	8.1
40	26	Round, corrugated	8 × 8	21	7.5
40	20 × 24	Rectangular	8 × 8	15	6.7
40	25 × 30	Rectangular	8 × 8	23	10.0
44	26	Round, corrugated	$6\frac{1}{16} \times 6\frac{1}{16}$	25	13.1

* BENT, Q., Modern Rolling-mill Practice in America, *J. Iron Steel Inst.*, **138**, No. II (1938).

After finishing the bloom, the roller whistles for another ingot and passes the bloom on down the delivery table to the blooming shear table where it is stopped and the end of the bloom which corresponded to the top of the ingot cropped back until the pipe is removed. The amount of cropping done depends upon the type of steel, the mold design, and the use to which the steel is to be put. The cropped ends usually fall through the table to a chute which dumps them into charging boxes for the open hearth. If the bloom is destined for the three-high billet mill, it is usually necessary to cut it into two or more lengths. In any case, enough is cut from the end of the bloom corresponding to the bottom of the ingot to square up the bloom, eliminate possible fishtailing, etc.

If the blooms are to be routed to the rail mill, they are pushed off the delivery table by a mechanical pusher and onto the transfer table. The transfer table may be merely an inclined framework down which the blooms slide or it may be horizontal

or nearly so and the blooms transferred by mechanical pushers. If the blooms are to be rolled on the three-high billet mill, they are conveyed on the roll table straight from the bloom shear to the mill and rolled to the desired size of billets. Here, also, the rolls are cooled with streams of water. In case a bloom at the shear must be cut into two lengths for rolling on this mill, the mill must be able to handle them at the same time in some such manner as that described previously. The runout table delivers them to either a shear or a hot saw which cuts the billet

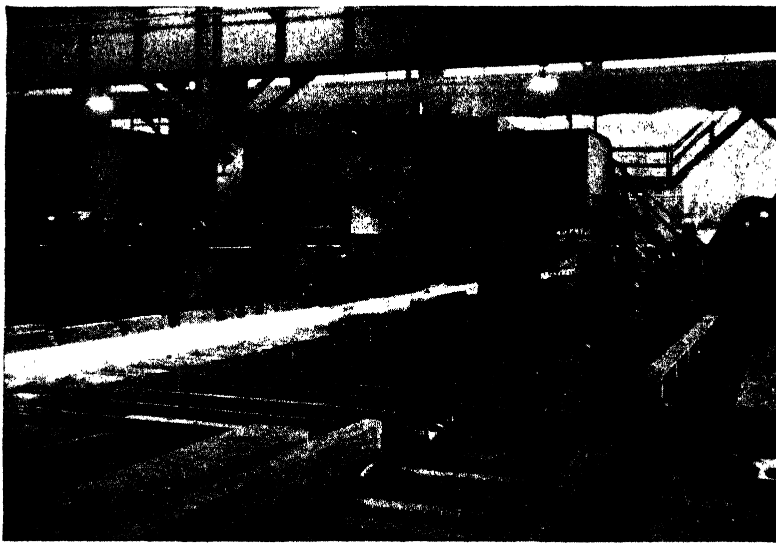


FIG. 10-XI.—A 1,000-ton bloom shear. (*Courtesy of The Mesta Machine Co.*)

into desired lengths. A hot saw is an electrically driven circular steel disk with coarse saw teeth in the edge. It rotates at a high speed and can be moved forward or lowered vertically to cut through the piece. This type of saw performs its work very rapidly.

If the blooms are to be rolled on the continuous mill the bloom is not cut into lengths but is cropped at both ends, kicked off on the transfer table, and deposited on the approach table of the continuous mill, from which it is fed into the first stand of the mill. A cropping shear is often provided just before the first stand to dress up the entering end of the bloom so that

it will enter the first pass easily. In rolling, the first two or three passes are usually box passes but the remainder are alternately square and diamond passes to finish the reduction to a billet of square cross section. The intermediate and finishing stands sometimes have two or four grooves of the same size cut in the rolls so that as one set of grooves wears too large, another set may be used without having to change the rolls. The rolls are water-cooled, and entering and delivery guides (twisting guides in some passes) are provided for all stands.

The billets are usually cut to length by a flying shear situated at the runout table of the mill, but sometimes the billets are cooled on a rack or hot bed and cut afterward to the desired length by a saw. When rolling blooms and billets, different types of surface defects occur which must be removed to a degree depending upon the surface requirements of the finished product. There are three general forms of surface preparation: grinding, chipping, and scarfing. The choice of the method used depends upon the capacity required, the quality desired, and the cost of preparation. The method used also depends upon the type of material to be treated. When it is necessary to eliminate small seams, the material is pickled before surface preparation.

Grinding as a means of surface preparation is limited to the harder grades of steel, where it is necessary because of exacting requirements to eliminate small surface seams.

Chipping is probably the most common method for the preparation of semifinished products. In the past, hand chipping with air hammers was the common practice, but this procedure is being slowly supplanted by mechanical chippers which will handle large blooms and can be used either to remove the entire surface or spot chip. For large defects in semifinished products a gouging machine has been developed, which is much more rapid in its operation than hand chipping.

Scarfing is becoming a popular method for surface preparation and consists of conditioning, either by hand or machine, with oxyacetylene torches. The procedure has been developed to a point where the product can be scarfed while it is being rolled on the mill. For example, a machine carrying a number of torches is used on carbon steel to hot-skin and remove the surface to a depth of $\frac{1}{16}$ in. from the four sides of the bloom surface. It is very important to have the proper handling equipment with this

procedure, otherwise scarfing has little, if any, advantage over chipping. It has been proved successful in conditioning grades of steel where the alloy and carbon contents are not excessive, and investigation indicates it will find wider application on other grades. In some mills the blooms are cooled and chipped (if necessary) and reheated for rolling into billets. This is particularly true of material when the surface of the finished product is of primary importance, and also of blooms for forgings. In most cases, however, the billet is rolled directly on the original heat of the ingot and the billet cooled and inspected. By the time the billet has been formed from the ingot, it is too cold for further shaping and must be reheated in any event before further rolling can be done on it.

Slabbing Mills.—Just as the bloom is the first step in the rolling of many shapes, the rolling of slabs is the first step in the rolling of plates. The reversing blooming mill meets all the requirements for rolling narrow slabs but the width of the slab that can be rolled in this way is limited by the maximum lift of the upper roll since the slab must be edged (turned on its edges and rolled in that position) in the last few passes in order to keep the edges parallel and flat. Wide slabs are rolled on slabbing mills specially designed with horizontal rolls to perform the main reductions and vertical ones to roll the edges of the slab.

Two types of horizontal roll installations are in use. In one type the horizontal rolls are arranged four-high, the plain, uncollared intermediate rolls being in contact with the slab during rolling and the two plain backing-up rolls being used for the purpose of stiffening the intermediate rolls. With this arrangement, the intermediate rolls can be made smaller in diameter than would ordinarily be the case in order to decrease the power required for a given reduction and the large backing-up rolls will prevent springing of the smaller rolls due to the bending effect which the metal being rolled exerts on the rolls. In this type, only the intermediate rolls are driven, the backing-up rolls being turned by frictional contact with the intermediate ones. In the other type, only two-high horizontal rolls are used, and they must be made stiff enough to withstand the bending effect. This can be done only by increasing the roll diameter and thereby increasing the power required for reduction. Four-high rolls are necessary only when it is desired to roll very

wide slabs. In either case, the rolls are adjusted by a screw-down mechanism as in the reversing blooming mills.

The vertical rolls are usually placed in a separate housing which may be connected to the main housing by tie bars. These rolls may be two-high or four-high with backing-up rolls, the former being much more common. These rolls are usually

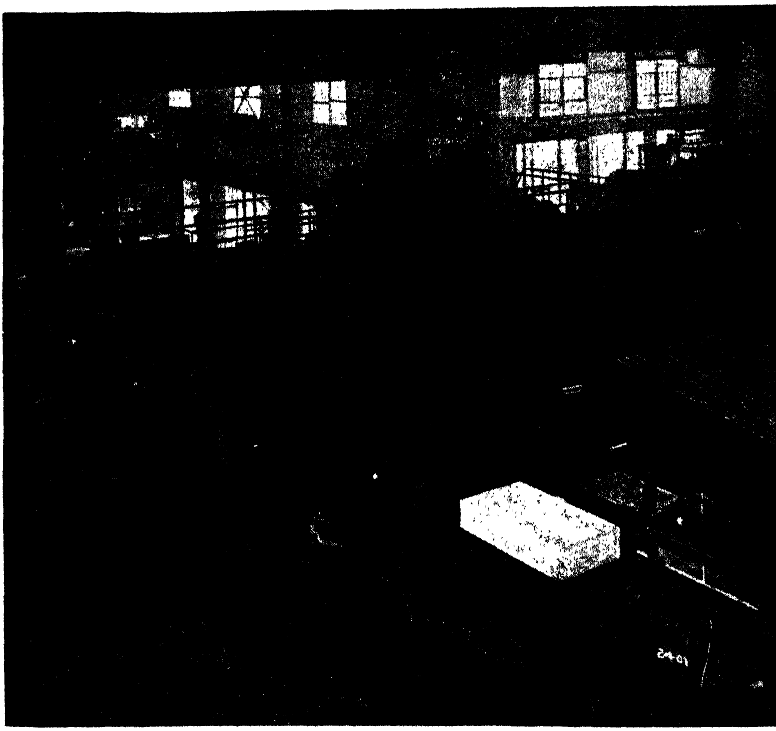


FIG. 11-XI.—A 46-in. slabbing mill in operation. (*Courtesy of The Mesta Machine Co.*)

about 7 or 8 ft. from the horizontal rolls and on either the entering or the delivery side. These vertical rolls are much smaller in diameter than the horizontal ones, usually being but a little more than half the diameter of the latter ones as the pressure exerted by them is small by comparison. They are slightly longer than the effective lift of the horizontal rolls, and the distance between them is regulated by a screw-down mechanism, very much like the one for the horizontal rolls. The

maximum lift of the upper horizontal roll limits the greatest thickness of ingot that can be rolled on the mill, while the widest separation of the vertical rolls limits the width of the ingot that can be rolled, as well as the widest slab that can be produced on the mill.

As both sets of rolls must be made to reverse their directions of rotation at the will of the operator, the drive is rather complicated. The vertical rolls are always separately driven. This is one of the main differences between the slabbing and the universal mill because in the latter the edging rolls are driven by the same engine that drives the horizontal rolls. A 44-in. two-high slabbing-mill installation has its horizontal rolls driven by a 10,000-hp. reversing twin-motor drive and the 26-in. edging rolls by a 2,500-hp. reversing motor, the edging rolls being placed on the delivery side of the mill. On odd-numbered passes (1, 3, 5, 7, etc.) the steel passes from the horizontal to the vertical rolls, and the entering speed of the vertical mill must equal the delivery speed of the horizontal rolls and, if a reduction is made by the vertical rolls, their peripheral speed must be higher than that of the horizontal rolls. This is true because if any reduction is made in the horizontal rolls, the delivery speed of the slab is greater than the entering speed due to the reduction. The edging rolls cannot turn slower than this delivery speed or the slab will buckle and, if they are turned much faster, the slipping of the edging rolls will tear the edges of the slab. In any odd-numbered pass, then, the desired speed of the edging rolls will depend upon the reduction made in the horizontal rolls and the reduction, if any, made in the vertical rolls, as well as the speed of the horizontal rolls. On the even-numbered passes the peripheral speed of the horizontal rolls must be greater than that of the vertical rolls, owing to the reduction in the vertical mill.

In the 44-in. slabbing mill referred to above, the load on the horizontal mill motors automatically determines the speed of the edging rolls on odd-numbered passes by an ingenious electrical hookup. In this way the load on the horizontal roll motors is adjusted, and the edging rolls are driven at the correct speed at all times. This mill is capable of rolling a 30- by 64-in. ingot and will produce slabs 60 in. wide by 4 in. thick at a maximum rate of 400 tons per hour. In operation, the roller controls the

direction and speed of the three main roll motors with a six-point foot-operated master switch, and controls the front and back main roll tables and the horizontal and vertical roll screw-downs with hand switches. His assistant controls the ingot transfer car, the approach tables, the side guards, and the manipulator. Older slabbing mills have their main rolls driven by a single engine or motor and pinion stand and the edging rolls by a separate power plant, the speed of these rolls being separately adjusted by the roller to suit conditions.

Plate Mills.—One of the important products rolled from slabs are plates. Steel plates comprise that group of hot-rolled finished steel products which are within the following specifications:

$\frac{3}{16}$ in. (0.1875 in.) or thicker, over 48 in. wide.

$\frac{1}{4}$ in. (0.250 in.) or thicker, over 6 in. wide.

Material thinner than this is classed as sheet and will be considered elsewhere. Other distinctions will be brought out later. Two methods of rolling plate are in general use in this country. One consists of rolling slabs in a special type of three-high mill and shearing the resulting plates to size, the product being known as *sheared plate*, and the mill as a *sheared plate mill*. In the other method, either slabs from the slabbing mill or slab ingots are reduced on a universal mill, the product being known as *universal mill plate*. The mills used in rolling both of these products will be described here.

The *sheared plate mill* (Fig. 12-XI), usually called the Lauth mill after its inventor, is designed to roll very wide plates. The size of the mill is designated by the length of body of the rolls, this length being a little greater than the maximum width of plate that can be sheared from the product of this mill. Mills up to about a 140-in. size are in use and it is evident that the rolls must be very strong and unyielding to overcome the tendency toward springing apart and thus producing a plate thicker in the center than at the edges. To minimize this springing tendency and at the same time reduce the power required for rolling with rolls of very large diameter, three-high construction is used. The top and bottom rolls are of the same diameter (about 40 in. in large mills) while the middle roll is between one-half and two-thirds the diameter of the large ones. In most cases, the two large rolls are driven while the middle one is friction driven. The upper roll can be moved vertically by means of an elec-

trically operated screw-down mechanism much like the ones used on reversing blooming mills. The smaller middle roll can be raised or lowered to come in contact with the upper and lower rolls, alternately. In this way, the middle roll is reinforced by the large rolls since, in making the bottom pass, the plate passes between the middle and bottom rolls and the top roll reinforces the center one. In making the return pass, the middle roll is dropped down upon the bottom roll and the piece passed between

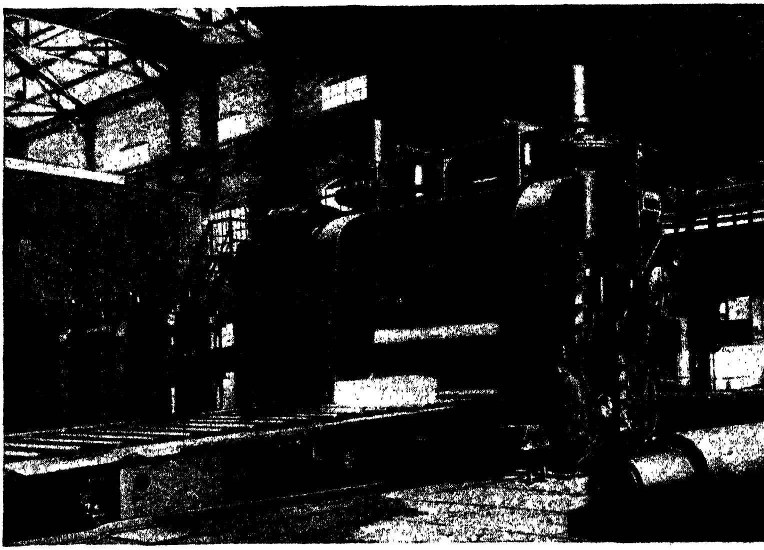


FIG. 12-XI.—A sheared plate mill in operation (upper pass). (*Courtesy of The Mesta Machine Co.*)

the upper and middle rolls, the bottom roll now acting as the reinforcing roll. The draft in each pass is controlled by the screw-down mechanism and recorded on a dial in view of the pulpit.

Even with this type of mill, some springing of the rolls occurs. In order to compensate for this, the middle roll is made slightly larger in diameter for a considerable distance at its center and then tapered down toward the necks. The rolls are made of cast iron and chilled to a considerable depth as they must be scrapped when they have been dressed down below the chill. The rolls are cooled by streams of water. This type of mill is usually electrically driven, the driving spindle being connected to the middle pinion which is an idler and imparts the proper

direction of rotation to the other two pinions and divides the power between them. In some cases all three rolls are powered, the center roll being directly connected and the two larger ones driven by a slip drive. In this way, the mill speed is regulated by the center roll and the outside rolls will not travel at a greater peripheral speed which, if allowed to occur, would curl the plate. Since the motor runs in one direction only, the operation of the mill is smoothed out by the use of a heavy flywheel mounted on the same shaft with the motor. In order to bring the plate to the upper and lower sides of the middle roll at will, tilting roll tables are provided.

Some sheared plate mills are made up of two stands of three high rolls arranged in tandem with a roll table between, each stand being provided with tilting tables on both sides. This arrangement has the advantage of greater tonnage since the first stand is used as a rougher while the second stand is finishing another plate.

The *universal plate mill* (Fig. 13-XI) is a type of reversing mill consisting of two horizontal rolls and four vertical rolls—two on each side of the horizontal rolls—all mounted in the same housings and all driven by the same motor or engine. This allows the production of a plate with rolled edges, but the mill is different from the slabbing mill in the features mentioned above. The size of this type of mill is designated by the greatest spread of the vertical rolls. These mills cannot roll plates of such great width as sheared plate mills, because of their different construction, the average size of universal plate mills being in the neighborhood of 44 in. With this size of mill, the minimum width of plate that can be rolled is from about 8 to 16 in.

The horizontal rolls must be long enough to provide the necessary working surface and extend across the faces of the vertical rolls as well, because the vertical rolls are set inside the housings and close to the horizontal rolls. For a recent 48-in. mill, the horizontal rolls are about 96 in. long in the body and 34 in. in diameter. The upper roll is moved vertically by a screw-down mechanism and both horizontal rolls are connected by spindles to a two-high pinion stand and driven as in usual reversing service. In some universal mills the power for the vertical rolls is taken from the upper pinion and conveyed, through an appropriate series of gears, to two drive shafts on

top of the housings, one being in front of and the other behind the horizontal rolls and parallel to them. Sliding miter gears on these shafts convey the power directly to the vertical rolls by meshing with crown gears keyed to the rolls. In this way, the vertical rolls can be driven at the same peripheral speed as the horizontal rolls and can still be spread apart or moved together by an electric motor at the will of the roller. In rolling,

FIG. 13-XI.—A 48-in. universal plate mill. (*Courtesy of The United Engineering & Foundry Co.*)

the vertical rolls on the entering side only are used to roll the edges of the piece since the vertical rolls do not run at a higher peripheral speed than the main rolls, and jamming of the plate would occur on the delivery side if the vertical rolls on this side were in contact with the plate. The rolling of the edges on the entering side is to be preferred because thin plates tend to buckle between the edging rolls if much pressure is applied.

The Manufacture of Plates.—As has been pointed out before, two types of plates are regularly produced: sheared and universal plates. The details of the methods involved will be briefly outlined at this time.

Plates may be rolled from ingots in one step as, for example, thick plates on the universal mill. It is more usual, however, to break down the ingot on a reversing slabbing mill, reheat without allowing the slab to cool to atmospheric temperature, and roll the slabs to plates on either the Lauth or the universal mill. For producing slabs on the slabbing mill, slab ingots are often used. These ingots are roughly rectangular in cross section but are much wider than they are thick, 30 by 64 in. in cross section being one of the largest sizes used (see Fig. 18-VII). It has been stated that narrow slabs can be rolled on the two-high reversing blooming mill but these slabs are not usually used for rolling into plate.

The slabbing ingot is usually fed to the slabbing mill with the small end first. The first pass is used mainly to square up the slab. The total draft made by the vertical rolls, rarely more than 1 to 2 in., is taken in the first few passes and from then on the pressure of these rolls is just sufficient to keep the slab from spreading farther. The heating of the ingot is of great importance because the temperature of the piece determines the draft that can be taken in each pass. Furthermore, the slab must be heated evenly throughout, because if the upper side is cooler than the lower, the slab will curl upward owing to uneven reduction. The curling can be prevented by rolling the slab with the hotter side up because the roll table will prevent the slab from curling downward. If one side of the slab is hotter than the other, it will curl laterally and cause much trouble. This also occurs if the rolls are out of alignment in any way. The maximum draft that the horizontal rolls can take is somewhat greater when the piece is passing from the horizontal to the vertical rolls, because the vertical rolls aid in pulling the slab through the horizontal rolls while, in the other direction, the vertical rolls cannot push the slab because of the danger of buckling. The last pass through the mill makes only a very small reduction because it is necessary to true up the slab, roll down the top ends and remove the convex surface caused by the springing of the rolls when heavy reductions are used.

While the slab is being rolled, the scale formed must be removed in order to prevent the slab and the resulting plates from acquiring a pitted surface. On low carbon steels, salt is thrown on the slab and high-pressure water sprayed on. The salt helps to keep the water on the slab until it can be drawn between the rolls.

In the case of high carbon and alloy steels on which scale is much more adherent, brush, twigs, or burlap is also used. This material is caught between the rolls, the high pressure and heat gasify it, and the gases carry the scale with them in escaping. Alloy slabs are turned over frequently with a crane and cleaned on both sides.

The finished slab is carried along the runout table to the slab shear where the pipe is first cropped off and then several slabs of the desired length are sheared off. The slab is then turned around, the necessary crop taken from the butt end and the rest of the slab cut into smaller ones of the desired size. The slabs are then reheated and are ready for the final rolling into plates on either the Lauth or the universal mill.

In recent years, the rolling of plates has been carried out on continuous mills which are also capable of rolling wide sheets. Typical examples of wide sheet mills which also roll plates will be discussed in connection with the rolling of sheet. In some other plate mill installations, the roughing of sheared plate is carried out on two-high reversing mills and the finishing on three-high mills of the Lauth type. In discussing the methods of rolling plate, only the simpler installations will be considered at this time.

The rolling of *sheared plates* is carried on in two stages: a roughing and a finishing stage. A separate stand is sometimes used for each stage but both can be done on a single stand. In the roughing stage, the slab is first given a few passes in a transverse direction (cross-rolled) to obtain the desired width and rolled longitudinally from then on. The amount of draft possible in one pass decreases as the width increases because the power required increases rapidly. The slab is rapidly worked down in the roughing stage to a thickness between $\frac{1}{4}$ and $\frac{1}{2}$ in. greater than the final thickness desired. The rest of the reduction is reserved for the finishing passes. The reduction carried out in each pass is quite small in order to finish the plate with the same thickness at the center as at the edges. The spring in the rolls becomes negligible at small pressures. In fact, no reduction at all is usually made in the last one or two passes. The same precautions as those used on slabbing mills are employed to eliminate curling of the plate and to remove scale.

From the rolls the plate passes over a roll table to a straightening machine. The roll straightener usually consists of nine

small rolls, five in an upper row and the other four in a lower row but staggered with respect to the rolls in the top row. The plate is given a large bend on entering the machine and this bend is gradually removed by giving the plate smaller bends until it emerges as a flat plate. Two or more passes are sometimes required if the gauge of the plate is heavy or it is too cold. From the straightening machine the plates pass to a cooling bed where they are cooled. They are then laid out with chalk

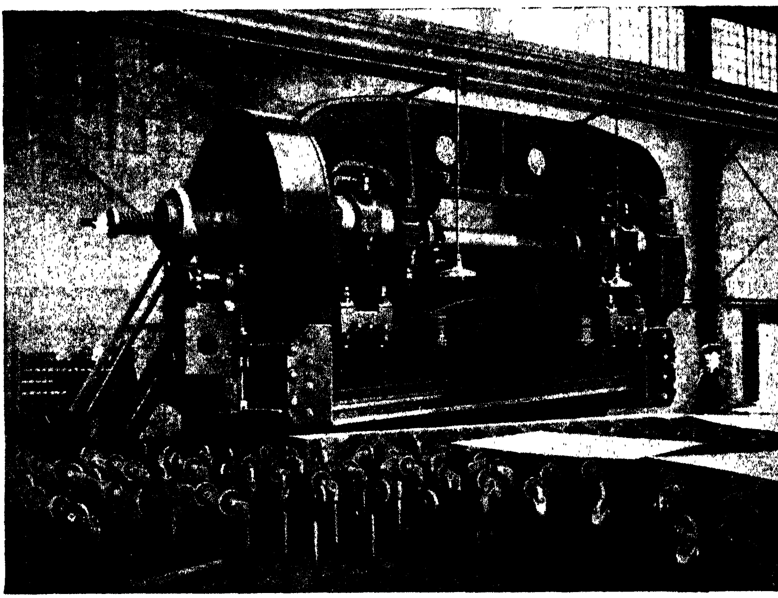


FIG. 14-XI.—A plate shear and shear table. (*Courtesy of The Mesta Machine Co.*)

lines for the desired size of plate. Sometimes the plate is rolled large enough to make two or more plates when cut, and rapid and accurate work is required of the man who lays out the plate for shearing. Allowance must be made for shrinkage as the plates are laid out before they are entirely cool. Three shears are provided in most cases, one on each side and one for the ends of the plate. The scrap is returned to the open hearth.

Universal mill plates are rolled much after the manner of sheared plates in regard to the method of reduction and the precautions necessary to prevent curling and excessive pitting. The width is set in the first few passes by the vertical rolls and

then kept at that value by slight pressure. These plates can be rolled directly from the ingot unless the plate is too thin to retain its heat for the time necessary for rolling. The only real disadvantage of rolling ingots on this mill is that a large amount of work is expended on rolling a portion of the plate that must be scrapped because it contains the pipe and badly segregated areas.

From the mill, the plates are straightened, cooled, and sheared to the desired lengths. Universal mill plates have certain advantages over sheared plates. Long plates with rolled edges can be produced for girder construction, for which sheared plates are not generally suitable. The cost of shearing and the scrap loss are much less for universal than for sheared plates and hence the cost of the plates to the consumer is less. Also, the universal mill is able to produce a greater tonnage of plates at the same cost. Sheared plates, on the other hand, have a big advantage in that they are cross-rolled in roughing the slab. Continued rolling in one direction only, as in universal mill practice, gives a product with flow lines running in the direction of the length of the plate, shown by a deep etch test upon a longitudinal section. It will also be found that the ductility will be greater in the direction of these flow lines than at right angles to them. Cross rolling of sheared plates eliminates this directional effect and produces material of uniform properties in all directions. Universal mill plates cannot be used when these uniform properties are required.

The production of *stainless steel plates* differs enough from that of ordinary steel plate so that the precautions necessary in producing them will be described as a typical example of the difficulties involved in handling large masses of high alloy steel. Large plates of this type are usually made of either an 18 per cent chromium, 8 per cent nickel, 0.10 per cent carbon maximum, balance iron, alloy, or of low carbon, 15 to 18 per cent chromium steel and are often used in the fabrication of equipment which requires the corrosion and/or heat-resistant properties of these alloy steels. Surface finish is of great importance and special precautions must be observed in preserving the surface during rolling.

The main differences from carbon steels encountered in rolling these steels lie in their greater stiffness or resistance to deformation and the small amount of scale produced on the surface. The scale formed, however, is very difficult to remove as it

sticks very tightly to the surface. The very much lower rate of heat conduction causes these steels to be very difficult to heat for rolling and causes additional problems in the rolling operation. These steels must be heated very slowly to about 2000°F. and can then be raised rather rapidly to a maximum of about 2250°F. The reduction of the ingot to the plate in one operation cannot be made because of the very coarse crystalline structure of the ingot which makes it very susceptible to cracking in the early

Fig. 15-XI.—Rotary flying hot shear. (*Courtesy of The Mesta Machine Co.*)

passes. The ingot is, therefore, worked down to about half its thickness with very careful manipulation and the resulting bloom slowly cooled. This rolling treatment also opens up all surface defects, which must be carefully chipped out. Grinding is often resorted to in order to remove enough surface metal to get below any decarburization because decarburized areas develop a large crystal structure that almost inevitably develops surface cracks on further rolling. All defects must be removed cleanly because the steel does not scale rapidly enough for the surface to be glossed over as often occurs in the case of plain carbon steels.

The slab is then reheated to the rolling temperature and in the case of sheared plate, carefully cross-rolled to obtain the

desired width of the plate. Salt and water or water-soaked bags are used in the first few passes to remove the scale. These high-alloy steels have such a high resistance to the penetration of working, owing to their stiffness, that they tend to elongate much more at the surface than at the center. When the slab is first cross-rolled and then turned for rolling to "gauge," the concave sides produced during cross rolling often cause serious scrap loss of valuable metal. After cross rolling, the procedure consists of rolling to the desired thickness as rapidly as possible. As 1700°F. is about the lowest limit to which rolling can be carried without detriment, the heat in the slab must be conserved as much as possible. This is accomplished by doing much of the rolling dry, *i.e.*, without drenching the rolls and slab with cooling water, as is done in the case of carbon steels. The amount of reduction that can be made per pass is about 60 per cent of that which can be safely used on plain carbon steels. This, of course, increases the number of passes necessary to produce an equal thickness. The thinner the plate and the greater the width, the more the dry rolling that must be used. Reheating operations on large plates are difficult and expensive and are avoided whenever possible. On the other hand, too much dry rolling may overheat the rolls and render them liable to breakage. Often carbon steel and stainless steel slabs are alternated, the rolls being drenched with water during the rolling of the ordinary steel slabs. In this way, the rolls are kept cool enough so that some dry rolling on the alloy slabs will not overheat them.

The Rolling of Duplex Plate.—The cost of high-alloy steels has restricted its use to a considerable extent except where its corrosion and oxidation resistance is absolutely necessary. Several methods are now in use for the production of duplex plate, which is a plate made up of a carbon steel plate with a thin plate of the heat- and corrosion-resisting alloy bonded to it. By substituting comparatively cheap carbon steel for a large portion of the stainless steel, a plate having the desired corrosion resistance is produced at a much lower cost per pound than if stainless steel were used throughout.

The following method[1] is used at one plant for the production of stainless clad plate coated on only one side. Two plates of stainless steel are rolled to a thickness considerably greater than

[1] TREMBOUR, M. R., *Iron Age*, **133**, 28 (June 28, 1934).

the thickness of the coating desired, cut to the desired size, and thoroughly cleaned. One side of each plate is coated with a special preparation which will prevent the surface from welding to any other surface. The two plates are then clamped together with their coated surfaces face to face and suspended in a slab ingot mold of such a size and shape that the plates do not touch the mold wall at any place. Molten low carbon steel is cast around them and, since the melting point of stainless steel is much above that of low carbon steel, the stainless plates do not melt but an excellent bond is formed between the plates and the low carbon steel. The ingot thus formed is rolled down to a plate of about twice the desired thickness and the excess low carbon steel trimmed off the edges so that the stainless plates are exposed. The plate is then separated along the juncture of the two inserted stainless plates which were prevented from welding together by the protective coating between them. The two plates resulting can be hot- or cold-rolled to final thickness and, when finished, present a highly finished and corrosion-resistant stainless steel surface on one side backed with cheap low carbon steel, the two being permanently bonded together. By using two or more such inserts in the mold, two or more such double plates can be made while plates clad with stainless on both sides can also be made by variations of this method. This same general method is often used to produce tools with tips of expensive high-speed steel bonded to shanks of cheaper and much less brittle carbon steel. Plates clad with hard steel for safes, and carbon steel plates clad with monel metal (a corrosive resistant nickel-copper alloy), pure nickel, etc., are also made by this method.

The Rolling of Rails and Structural Shapes.—The rolling of railroad rails and all but the heaviest of the structural shapes (I beams, H beams, channels, etc.) is done in much the same way and on the same type of mill. In fact, the same mill setup is used for both, the rolls being changed for the different sections. The rolling of rails will be described as an example of manufacturing these shapes and the following typical example[1] is used.

The ingot is first broken down to a 10- by 11-in. bloom. The bloom is very carefully cropped and then cut into two blooms of about 3,700 lb. each. The blooms are reheated and each is rolled on the rail mill to a 130-lb. per yd. rail (one of the standard

[1] KENYON, A. F., *Blast Furnace & Steel Plant*, **19**, 832 (June, 1931).

sizes) in eleven passes. The 85-ft. length is cut into two standard 39-ft. rails, cooled on the hot bed, straightened, the bolt holes drilled, and given final inspection for shipment.

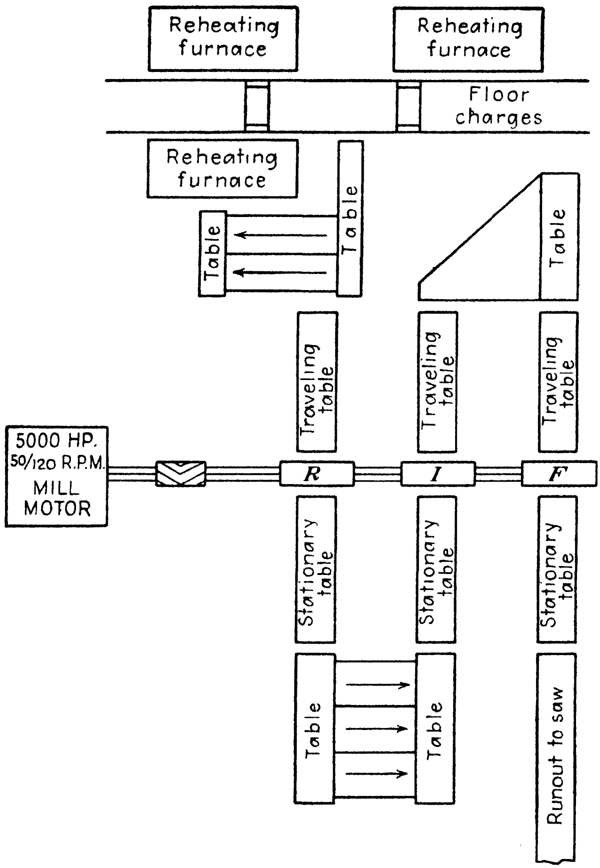


FIG. 16-XI.—Setup for a rail and structural mill. *(From Blast Furnace and Steel Plant.)*

The setup of a typical mill for rolling the blooms is shown in Fig. 16-XI. The mill is made up of three stands of three-high rolls arranged in train and driven through a 30-in. pinion stand by a 5,000-hp. motor connected to the center pinion by a spindle and universal couplings. In rolling rails only one pass is needed in the last stand so it is set up two-high and, when structural

shapes are being rolled, it is replaced by a three-high set. The roughing and intermediate three-high stands are equipped with 31-in. diameter by 68-in. rolls and the two-high finishing stand with 31-in. diameter by 36-in. rolls. Three traveling tilting roll tables are provided on the entering side of the mill and three stationary tilting tables on the delivery side. In rolling rails, all transferring from one stand to another is done on the entering side of the mill. In rolling some structural shapes, it is necessary to transfer from the roughing to the intermediate stand on the delivery side of the mill. For this reason, roll tables and a chain transfer connect them. A stationary table and side extension back of the tilting table on the entering side of the finishing stand take care of the lengthening of the rail in the last pass or two. Three reheating furnaces with machine chargers furnish the mill with heated blooms, the blooms being placed upon the approach table to the mill at intervals. The mill is also served by large cranes which are capable of lifting a complete three-high stand, equipped with guides and guards, and of placing it on the mill shoes when roll changes are to be made.

In rolling, the first traveling table receives the bloom from the approach table and takes care of it for the first five passes in the roughing stand. At the end of the fifth pass, the piece is on the delivery side of the mill and the first traveling table moves over to the approach table for another bloom while the second table takes its place to receive the piece after the sixth pass. The second table then transfers the bloom to the intermediate stand and handles it during the seventh, eighth, and ninth passes, at the end of which the piece is again on the delivery side of the mill. The second table is then moved back to the roughing stand and the third table receives the piece from the tenth pass (the last in the intermediate stand) and then transfers it to the finishing stand where the last pass (eleventh) is made, the finished rail being passed on the runout table to the saws. In this way, the mill is capable of handling a piece in each stand almost continuously and operates at the rate of 150 gross tons per hour. The master switch for the main motor has five speeds between zero and 50 r.p.m., while pushing a button in the pulpit will decrease the mill speed for the first few passes in the roughing stand. When the button is released, the mill automatically accelerates to the usual running speed.

The rolls from a four-stand rail and structural mill, but set up for rails, are shown in Fig. 17-XI and indicate clearly the shape of the various passes. The two lower stands are driven by a single motor and three-high pinion stand, and the other two stands are similarly driven. The two trains are separated by tilting roll tables and stationary tables of sufficient length so that the piece is out of one train before it enters the next. A transfer table connects the two tables on the delivery side of the upper stands.

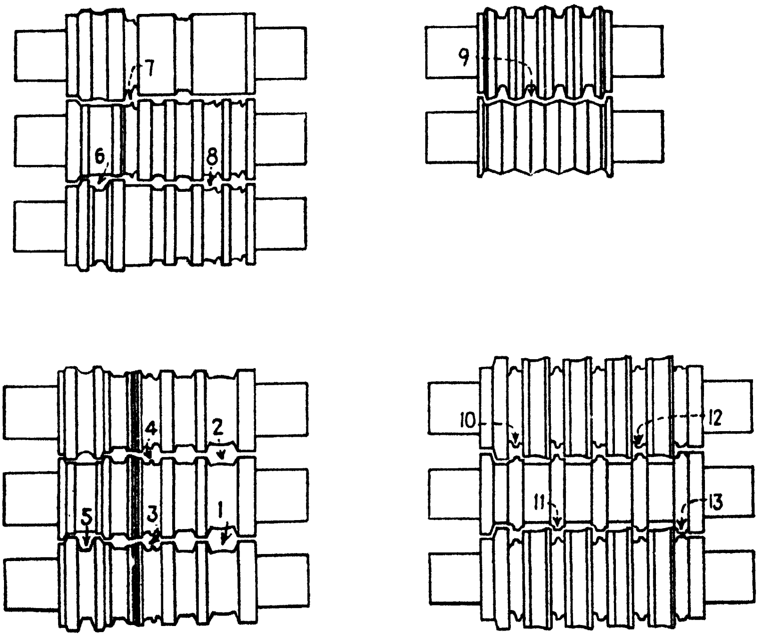


FIG. 17-XI.—Rolls for a rail mill. (*After Stoughton.*)

If the rails are to be heat-treated, they are quenched in a tank of oil either before or after sawing to appropriate lengths. If not quenched, they are sawed and conveyed to the cooling tables where they are cooled in air. The rails are then straightened in a gag press, which consists of a heavy bottom frame on which the rail is supported at two points near the ends and a heavy block which is movable along the rail and is capable of being driven downward to bend the rail at the desired points in order to straighten it. After this operation the rails are inspected and,

if they pass, the holes for the bolts are drilled at the ends and the rail is ready for final inspection and shipment.

Whereas small and intermediate sizes of structural members are produced much as given above for rails, the very large sizes are rolled on an entirely different type of mill. (In fact, before the development of this type of mill, these large beams had to be built up from plates and angles.) Such a mill,[1] designed for the production of wide flange H beams, will be briefly described and its method of operation indicated. This mill is capable of producing beams with flanges up to 15 in. in width, weighing up to 425 lb. per ft. and was designed for 26,000 tons per month.

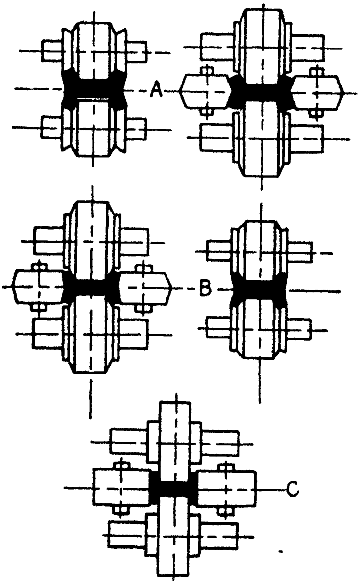


FIG. 18-XI.—Rolls for producing large H beams. (*From Iron Age.*)

The mill itself is fed by a 54-in. reversing blooming mill, electrically operated and fully equipped with all necessary auxiliaries. On this mill, the ingot is broken down to a beam blank, the rolls having a bullhead in the center and grooves for forming the blanks on either side of the center pass. It is driven by an 8,000-hp. reversing motor. An electrically driven shear is located on the delivery table leading directly to the roughing stand of the beam mill. The roughing stand is located about 300 ft. from the blooming mill, while the intermediate stand is nearly 200 ft. beyond the roughing stand, and connected by a roll table. The finishing stand is located over 200 ft. from the intermediate stand, while the runout table to the hot saw is 208 ft. in length. The roll tables, saw, transfers, and manipulators for the blooming mill are all electrically driven.

The roughing and intermediate stands are rather complicated. The roughing stand, shown in *A* of Fig. 18-XI, is really composed of two stands of rolls in tandem: an edging stand and a main stand. The edging stand has horizontal rolls and is so called

[1] KOON, S. G., *Iron Age*, **121**, 1380 (May 17, 1928).

because it works only on the edges of the flanges of the beam. The two main rolls of the other stand of the roughing set work on the web and inside faces of the flanges in the manner shown, while vertical rolls, set between the roll necks of the horizontal rolls, work on the outside faces of the flanges. The two stands of the roughing set are placed 12 ft. apart, the edging stand being on the entering side of the mill. Each stand is separately driven. The edging stand is driven by a 2,000-hp. reversing motor and is equipped with a screw-down mechanism. The main stand is driven by a 7,000-hp. reversing motor, and both the horizontal and vertical rolls are equipped with screw-downs. Both stands are connected to 52-in., two-high pinion stands which are in turn connected to the motors. The vertical rolls in the main stand are not driven but are set in tapered roller bearings and are turned by the friction of the piece passing between them. The electrical hookup between the two stands is very ingenious as the speeds of the two driven pairs of rolls are automatically regulated so that when the piece is in both stands at once, it is neither stretched nor buckled. The intermediate stand, *B* of Fig. 18-XI, is constructed just like the roughing stand with the exceptions that the edging stand is located on the delivery side and the flare of the flanges is not so pronounced. The flare is accentuated in the drawings in order to show the principles of the rolling operations. The finishing stand, *C* of Fig. 18-XI, is composed of a set of horizontal rolls, driven by a 5,000-hp. nonreversing motor and a 52-in. pinion stand, and a set of vertical idlers, both pairs of rolls being controlled by screw-downs. This stand is used to bring the flanges parallel to each other and perpendicular to the web portion of the beam. It is not reversing as only one pass is made in it.

In the operation of this mill, the beam blank is passed along the roll table to the edges of the roughing set which grasp it, roll the edges of the flanges, and feed it to the two pairs of rolls of the main stand. The piece is fed back and forth through both of the roughing stands nine times, the screw-downs being operated on all three pairs of rolls after each pass. The driven rolls work on the web and insides of the flanges and the idlers upon the outsides of the flanges. The automatic drive turns the edging stand at the correct speed to suit the velocity of the piece, regardless of the direction in which the piece is traveling or the amount of

reduction in the main stand. Another automatic feature of both this and the intermediate stand is the automatic screw-down mechanism. The mill can be set in advance for a certain desired amount of screw-down on each of the three pairs of rolls for each of the eight passes after the first. During rolling, the roller merely pushes a button after each pass and the three screw-downs are automatically operated to give the desired reduction in the next pass.

After the nine passes in the roughing stand, the roughed-out beam is passed along a roll table to the intermediate stand where five passes are made, the automatic screw-down being operated and the mill motors reversed after each pass. The piece is then given one pass through the finishing stand and sent along the delivery table to the hot saw. The edges of the flanges are not rolled in the finishing stand but, as the beam is given the last pass in the intermediate stand, the edging stand, being on the delivery side of the mill, rolls the flange edges just before the beam passes to the finishing stand. In all the stands, the rolls are cooled with water, and steam jets blow the scale off the metal. The entire operation is carried out on the original heat of the ingot and is controlled by only four men from the time the blank leaves the bloom shear until it reaches the hot saw. The beams are finally cooled on cooling tables, straightened on gag presses, and inspected before shipment.

Merchant Mill Practice.—The subject of merchant mills and their products is a difficult one to discuss adequately because of the wide variety of both mills and products. In the early days of the steel industry, the merchant mill was a single stand of three-high rolls, regularly rolling a variety of simple shapes which were stocked and sold as ordered. The rapid strides in the use of steel as well as in the methods of making and fabricating it caused the single stand to be rapidly outgrown because it did not offer enough passes to form the more complicated sections desired. At the same time, the manner of carrying on the business changed, the mills rolled a section only as ordered, instead of keeping a stock on hand, so the term "merchant mill" lost its meaning. This term is still used, however, to designate a rather small size of mill which regularly rolls more than one section and includes all the types of mills that were briefly described in the introduction to this chapter, as well as combinations of these

and a few special types. Figure 19-XI shows much better than words can express the wide variety of merchant mill products in use today. It is not to be inferred that all or even most of these products are rolled on one mill. In fact, Fig. 19-XI represents the products of eleven different units.

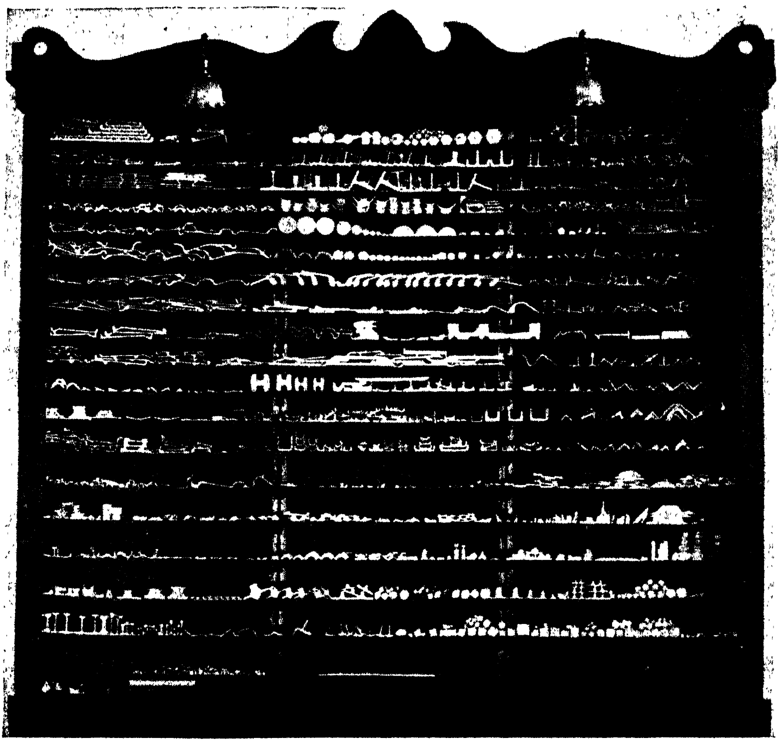


FIG. 19-XI.—Merchant-mill products. (*Courtesy of The Carnegie-Illinois Steel Corp.*)

A typical example of a merchant mill[1] is shown in diagrammatic form in Fig. 20-XI. The continuous rougher consists of six 14-in. stands arranged in tandem and driven by a 1,500-hp. motor and gear train, each stand being driven enough faster than the preceding one to take up the slack. The roughing set is fed with heated billets by continuous furnaces and a roll

[1] LONGENECKER, CHARLES, *Blast Furnace Steel Plant*, **18**, No. 1, 153 (January, 1930).

table. A crop shear is located in front of the first stand of the rougher to true up the end of the billet. The partly reduced billet emerges from stand 6, is run out on the roll table and, after its direction of travel is reversed, is fed back through stand 7, which is driven by the same motor that runs the roughing set. Transfers in the roll table move the billet over in front of stand 8 (also 14 in.) and reverse its direction of travel again. A repeater receives the bar from stand 8 and enters it into stand 9. The bar is now flexible enough to be looped through the rest of the stands. Stands 9, 10, 11, and 12 are 11-in. stands and are driven, with stand 8, by an 1,800-hp. motor. If the piece is

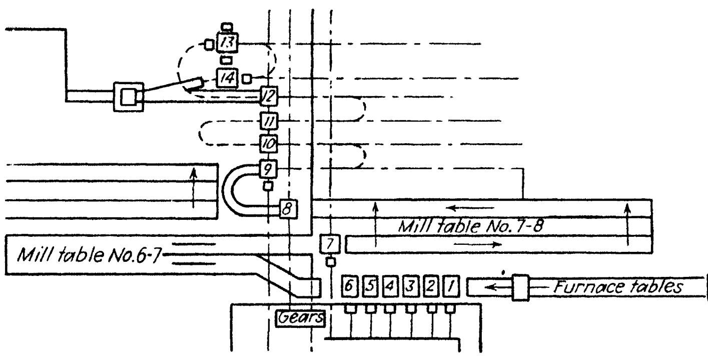


FIG. 20-XI.—Diagrammatic sketch of a merchant mill. (*Blast Furnace and Steel Plant.*)

finished in the stand 11, it is delivered by a table to a hot bed. If further passes are necessary, the bar is looped through stands 12, 13, and 14 in succession, the last two being 8-in. stands driven by an 800-hp. motor. The product of the mill includes rounds from $\frac{3}{8}$ to $\frac{3}{4}$ in.; squares from $\frac{3}{8}$ to 2 in.; flats from $\frac{3}{8}$ by $\frac{1}{4}$ in. to $2\frac{1}{4}$ by $\frac{1}{4}$ in.; concrete bar from $\frac{3}{8}$ in. to $\frac{1}{4}$ in. round and square; and bumper stock from $1\frac{1}{2}$ to $2\frac{1}{4}$ in. wide and of various thicknesses. This gives an idea of the versatility of the modern merchant mill.

In mills of this type where looping trains are used, it is obvious that some means must be used to reverse the direction of rotation in each succeeding stand. The common way of doing this is to construct the roll housings three-high for all the looping stands but place only two rolls in each housing and run a shaft through the housing in place of the third roll. All the stands in the train

are then driven by a three-high pinion stand from a single motor. For example, in the first stand the middle and bottom rolls form the passes while a shaft runs through the housing in place of the top roll and connects to the top roll of the second stand. In this second stand, the top and middle rolls form the passes and a shaft runs through the housing in place of the bottom roll. The direction of travel of material through the two stands is reversed in this way. This arrangement can be modified slightly by making the top and bottom rolls dummy rolls in alternate stands. In some other cases, gear arrangements are used to reverse the direction of rotation of succeeding stands of two-high rolls when placed in train and driven by a single motor.

In the case of merchant mills rolling the larger sizes of products and particularly in rolling alloy steel bars of various sizes where high rolling speeds are neither necessary nor desired, two-high stands are sometimes arranged in train and driven by a reversing motor. In one mill of this type, four two-high stands are driven in train by a single reversing motor. Each stand is equipped with approach and delivery tables, each roller being set with its periphery just above the floor plates in order that the mill crew can handle the billets between passes. Motor-driven side transfers are employed to skid the billets from one table to the next. These transfers have the form of steel fingers which rise through slots in the floor plates, engage with the bar, and transfer it to the next stand. In rolling, a billet is brought on approach tables to the roughing stand located at one end of the train and passed back and forth through several passes in the roughing stand while one of the mill crew stationed on each side of the stand turns the piece after each pass and guides it into the proper groove. The whole train of rolls is reversed for each pass. The last roughing pass leaves the piece on the delivery side of the mill and, after transfering the bar to the first intermediate stand and reversing the mill, the piece is given its initial pass in the first intermediate stand. The mill is again reversed and, when the bar is entered into its second pass in this stand, a new billet is started in the roughing stand and both of them passed back and forth together. The same is true of the second intermediate and finishing stands, except that only one pass is usually made in the latter, and a piece can be rolled in each stand at once. The operation of the mill motors, transfers, roll

tables, approach and delivery tables is under the control of the pulpit operator. This type of mill is suited to the rolling of large sections that do not cool rapidly or to classes of steels that require slow rolling speeds.

In contrast to the foregoing, high-speed continuous mills are sometimes used in the production of bars and other simple sections of small sizes. One typical installation[1] of this type is designed to roll various sizes of rounds, squares, hexagons, flats, concrete reinforcing bars, etc., and will be briefly described. The mill consists of 12 two-high stands of rolls arranged in tandem and directly connected by a roll table with a continuous heating furnace. The first breakdown stand carries 16-in. diameter by 36-in. rolls and operates at a speed between about 10 and 40 r.p.m., depending upon the section being rolled. The next four standards of 14-in. diameter by 36-in. rolls step up the speed of rolling to a maximum of slightly over 180 r.p.m. in the fifth stand. The next three stands are 12-in. diameter by 30-in. rolls, and the rolling speed is further increased. Owing to the difficulties of twisting the bar between passes at the high speeds used in the finishing stands, the last four stands have alternately horizontal and vertical rolls. In vertical stands 9 and 11 the motors are mounted on their sides, vertically over the rolls, and drive them as in an ordinary horizontal installation. Provision is made for shifting these rolls both vertically and horizontally to line them up for different sections. The rolls in the vertical stands are 11½ in. in diameter while those in the two horizontal finishing stands (nos. 10 and 12) are 10-in. diameter rolls. Each stand is driven by a separate motor, all the speed relations being synchronized. The last stand operates at a maximum speed of about 750 r.p.m. From the last stand, the bar goes either to the flying shear and cooling beds or through tubes to special coiling apparatus where it is coiled and discharged onto conveyers.

The designing of merchant mills is a difficult proposition and requires a great deal of experience on the part of both the roll designer and the staff that designs the mill as a whole. The mill must be designed to operate very rapidly in nearly all cases as the sections are small and cool rapidly. At the same time, the final product must be very accurate in size and section. As the speed increases, this becomes more and more difficult to accom-

[1] GERKEN, T. H., *Iron Age*, **130**, 644 (Oct. 27, 1932).

plish. The roll designer is always under pressure to limit the total number of stands in a mill to the minimum figure and to provide for the maximum number of different sections, as well as different sizes of the same section on one mill with a minimum number of roll changes. For this reason, grooves corresponding to several sizes of the same section and sometimes to sizes of slightly different sections will be cut side by side in the same pair of rolls. The cost of extra sets of rolls is very high when it is considered that they are idle most of the time and that valuable time is lost in shutting down the mill for roll changes.

It should be noted that the roughing set of the merchant mill has to be designed very carefully because as many different finished products as possible are desired from the material emerging from the roughing rolls. It is usually desired to roll all the products of a merchant mill with only two different sets of roughing rolls, in order to minimize the expense of extra rolls and roll changes. The designer is limited, therefore, in designing the roughing set and must choose with care in order to have the piece issuing from the roughing rolls of such size and shape that it will be adaptable for the production of the widest variety of finished sections. As has been inferred before, the first few passes which reduce the size of the section but make little or no change in the shape are called *roughing* passes. If this same procedure is continued to smaller sizes, these next passes are called *pony roughers.* The passes that do most of the shaping of the article are called *strands,* while the one just before the last is called the *planishing* or *leader* and shapes the piece entirely or very nearly to its final size and shape. Almost without exception, the last or *finishing* pass merely removes the irregularities of previous rolling and no reduction is normally made in it. This prevents rapid wearing of this pass which must be absolutely true in order to roll an accurate section.

Particularly at high speeds, but almost equally true at all speeds of rolling, the actual operation must be very carefully watched or defects will occur which necessitate the scrapping of finished or nearly finished material. The rolls must be perfectly aligned in all cases or the piece will twist in the rolls, fail to fill the groove properly, or cause trouble with the guides. The entering and delivery guides must be carefully adjusted to prevent guide marks and tearing of the metal and to support the piece

in the pass properly. In some cases where an especially smooth finish is desired, precautions are taken to remove the scale before the planishing pass. Some sections can be scraped to remove the scale, others can be given a slight double bend to crack the scale and steam or water used to blow it off the surface. The finishing temperature is kept as low as possible in these cases to prevent the formation of scale when the material is delivered to the cooling bed.

Reheating Operations.—Most finished articles require one or more reheatings during the rolling or forging process. Even with the very rapid modern methods of fabrication, most finished products are of too small a section to be shaped directly from the ingot without becoming too cold for proper forming. Some few heavy finished products, such as big rails, heavy plates, and large structural shapes are of such large sizes that they are capable of being rolled on the initial heat of the ingot. Practically all other products require at least one reheating operation as an important step in their manufacture.

Two main types of furnace are in use for reheating blooms, billets, and slabs to hot-working temperatures: the continuous furnace and the regenerative batch furnace. Neither of these is at all standardized, each furnace being designed for a particular job and differing in details of construction from most other furnaces of the same general type. Before proceeding to a general description of these furnaces, it is believed to be better to consider reheating operations in a general way and then describe and compare the furnace types in the light of the principles involved.

One of the most important functions of a reheating furnace is to heat the steel to the desired temperature. In most cases, it is necessary to heat steel very close to the upper limit of the hot-working range where there is considerable danger of overheating and burning the steel if the furnace is incorrectly designed or operated. The best method available for regulating furnace temperature is through automatic regulation by means of a thermocouple installation which, in turn, controls the fuel supply through an appropriate electrical hookup. The only method of determining the steel temperature is by means of an optical pyrometer. This method is unreliable except possibly in the hands of an expert. It is much more satisfactory to adjust

the furnace temperature to a value where the steel reaches the desired temperature and then automatically maintain the furnace at that temperature. It is obvious that the steel can never reach a higher temperature than the furnace and, if the furnace temperature is kept below the danger point, one can be certain that the steel will not be burned if the furnace temperature is uniform.

If steel is heated too rapidly, it is apt to crack owing to uneven or too rapid expansion. The penetration of heat into steel of large cross section is surprisingly slow, and the application of heat must be carefully controlled if the steel is not to be injured. The larger the section being heated and the colder it is, the more gradually the heat must be applied to it. The greatest danger of cracking occurs when steel is rapidly heated (or cooled) below 1200°F. Above this temperature the rate of safe heat penetration is greater. Carbon steels can be safely heated at the rate of about ½ in. of thickness per hour. Therefore, an 8- by 8-in. bloom, heated equally from two sides, can be brought safely to an average hot-working temperature in about 8 hr. If several pieces are touching and resting on a cold furnace bottom, a considerably longer time is needed. Alloy steels and high carbon steels have such slow rates of heat penetration that it is often advisable to preheat them slowly to above 1200°F. in a low temperature furnace and then transfer them to the high temperature forging or reheating furnace. It is also very necessary to have the temperature of the heating chamber of batch furnaces as even as possible in order to avoid possible overheating of some pieces and uneven heating in general. The pieces being heated must be turned at intervals to allow heat to penetrate from all sides. The heating procedure is most correctly carried out when the piece is gradually brought to temperature in such a way that it is heated evenly from outside to center to the desired value. It is also important that the furnace be so designed that it is capable of properly heating enough steel to take care of the full capacity of the forging machines or rolling mills for which it furnishes steel.

It is practically commercially impossible to avoid some scaling in heating steel to high temperatures. The higher the temperature, the longer the time at that temperature, and the more oxidizing the furnace atmosphere the greater will be the amount

of scale produced. In addition, an oxidizing atmosphere burns carbon out of the steel, producing what is called a "decarburized" rim. Both scaling and decarburization are detrimental, the former because it represents a loss of metal and the latter because it produces nonuniformity in the metal.

Scaling can be reduced in several ways. The use of an atmosphere of raw gas in the heating chamber in addition to the products of combustion or the placing of charcoal or coke in the chamber to produce an excess of CO is often advocated. Modern furnaces are usually kept under a slight pressure to prevent excess air from leaking in around doors and scaling the steel.

Economy in fuel consumption is also a very necessary quality in a heating furnace or the operating costs will be excessive. This can be attained by using the most economical fuel for a given locality and type of operating condition, by economical combustion conditions, by transferring the largest possible percentage of the heat produced to the steel, and by utilizing the heat escaping with the waste gases. A slight excess of air over that theoretically required for combustion is necessary for economical fuel consumption, while intimate mixing of fuel and air and the use of preheated air are also requisites. The waste heat contained in the stack gases can be utilized by installing waste-heat boilers and regenerative or recuperative systems.

The *regenerative batch-type reheating furnace* (Fig. 21-XI) is similar in principle to the open-hearth furnace. Gas and air ports at either end of the furnace and two sets of checker chambers are provided if gas is used as a fuel. Valves for reversing the flow of the gases are required. The hearth of the furnace is flat and is usually equipped with rails set on it to keep the steel from coming into contact with the hearth. A low bridge wall prevents the hot gases from playing directly upon the steel but forces the flame to pass just above the steel and heat it principally by radiation. Large lifting doors on one or both sides of the furnace permit the charging and withdrawal of material, this usually being done by machine. The hearth is usually built up of magnesite which, after being contaminated with scale and worn out, can be charged into the open-hearth or blast furnace and the iron recovered. The walls and roof are constructed of a good grade of silica brick. The size of this type of furnace varies widely with the type of work it is required to do.

The *continuous furnace* is based upon the countercurrent principle and, in addition, is equipped with a recuperator. This type of furnace has a very much greater length than either width or height. At one end of the furnace is located the combustion chamber. The hot gases from the burning fuel pass over a low bridge wall and through the heating chamber in which the steel is located. At the other end of the furnace the gases pass down through a flue set in the hearth, through a set of steel or refractory tubes arranged in parallel, and then up the stack. The air for combustion is preheated by forcing it to flow around the series

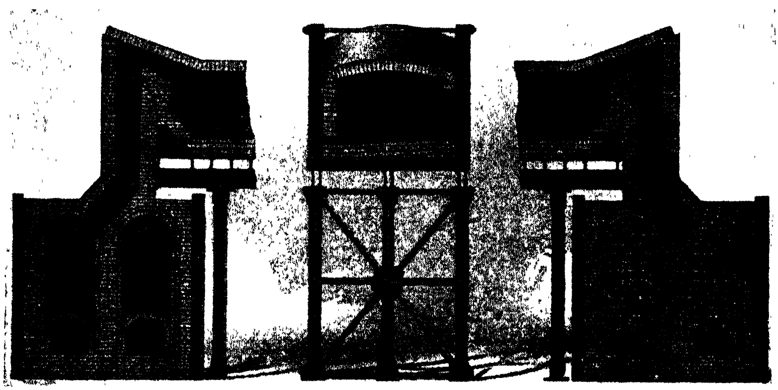


FIG. 21-XI.—A typical gas-fired regenerative heating furnace. (*Courtesy of Harbison-Walker Refr ctories Co.*)

of tubes (the recuperator), then under the hearth of the furnace for its entire length where the air picks up more heat, and then through an underground flue to the back of the combustion chamber where it is mixed with the fuel for combustion. The steel enters at the same end of the furnace as the air and is pushed by mechanical pushing or conveying devices through the furnace until the pieces emerge one by one through a door under the combustion chamber. In this way, the passage of hot gases is made countercurrent to the passage of air and steel and all are made continuous in operation.

Although the furnace is usually made only slightly wider than the length of bloom or billet being heated, some furnaces are designed to heat two lines of material at once. For high temperature service, water-cooled skids are placed lengthwise on

the hearth on which the metal is supported well above the hearth. The height of the heating chamber is rather small in order to force some of the hot gas under the steel and thus heat it from the bottom. In operation, a bloom or billet is placed on the skids, a hydraulic ram pushes it into the furnace, another billet is placed at the entrance, and the ram pushes it in also. This procedure is repeated and the line of pieces, each one against its neighbor, is slowly pushed through the furnace until it is full. From then on, whenever a piece is pushed in at one end of the furnace, a heated piece is also pushed off the ends of the skids at the other end and usually slides down an incline and onto a roll table. If the furnace is designed for rounds, the hearth is sometimes tilted up slightly toward the combustion chamber to keep them together, but for square or rectangular sections the hearth is usually tilted downward to save power in pushing the material through. It can be seen that the length of the furnace and the rate of travel determine the time the metal is heated. Different heating times can be obtained by varying the speed of travel, and different final temperatures of the steel by adjusting the combustion conditions.

The continuous furnace has several decided advantages over the regenerative batch furnace. Uniformity of finishing temperature of heating of all pieces and uniformity of the temperature of any one piece are important advantages of the continuous furnace. Also, the steel can be heated as slowly as desired because the cold steel enters at the cool end of the furnace and, as it is heated, it comes in contact with hotter and hotter surroundings until it emerges from the furnace. Since the temperature difference between the piece and its surroundings is never very great, the dangers of cracking and cool centers are minimized. Furthermore, the fuel and labor costs for continuous furnaces are much lower than for batch furnaces of the same daily capacity. The fact that the continuous furnace can be made entirely automatic in operation, both as to charging and discharging and in the regulation of temperature and combustion conditions, weighs heavily in its favor. In fact, batch-type furnaces are slow, inefficient, and uneconomical for heating cold billets and blooms of large size and are mainly used at the present time for giving "wash" heats—raising the temperature only 300 or 400° so that the furnace may be maintained at the desired rolling or

forging temperature and not have to be cooled for the introduction of cold metal. Continuous furnaces are used almost without exception for serving continuous mills.

Pickling of Iron and Steel.—Many of the finished grades of steel that are accepted as normal steel mill production could not be manufactured without the removal of scale between various operations, were it not for the cheapness and the efficiency of the operation known as "pickling." Pickling may be defined as the chemical process of removing scale or oxide accumulated on the surface of iron or steel as the result of a heating operation. It is necessary to remove this scale as well as any other foreign substance that may be on the surface before further processing or coating. Pickling in an acid solution is the most rapid and most economical method universally used. The general procedure in pickling is to submerge the material in an acid bath until free from scale, after which it is removed and given a thorough rinse and neutralization to remove all traces of acid.

Pickling appears to be a simple process, but in many instances certain refinements or modifications are necessary because of variations in scale formation and differences in processing practice and in equipment encountered even in two plants making the same product; hence, it is not practical to reduce pickling procedure to a standard formula. In some instances the problem has become so complicated that the theories involving scale removal have become controversial. Therefore, the following discussion of theories and practice will serve to illustrate general features involved in this problem rather than formulas for procedure.

There is a wide variety of steels being pickled which vary as to chemical and physical properties. These variations, although not numerous, are in part responsible for many of the difficulties encountered. For example, it is found that steels of the same analysis will pickle differently. This variation is dependent upon the processing, the stresses resulting from the processing, the rates of cooling from the various operations, and the heat-treatment. The character of the surface of the work to be pickled must be considered. Cleaning prior to pickling is often as important as the operation itself. Frequently, during the fabricating process, the product becomes covered with a film of oil or grease which is not soluble in the acid pickling bath and if not removed

will retard the pickling action. The most general procedure is to dip the metal in a hot alkaline solution and follow with a very careful rinse before placing it in the acid.

Heat-treated materials also introduce many special pickling problems. Alloy steels when heated above a certain critical temperature which varies with the type of steel will, when pickled, set up an electrolytic action which proceeds at the expense of the clean metal and results in deep pitting of the surface. Scale produced in the normalizing of steels is the most difficult to pickle as far as time in the bath and pitting are concerned; while scales produced by tempering are the easiest to handle.

Pickling Solutions.—The kind of acid used depends entirely upon the article to be cleaned and the results desired. Sulfuric acid is the one most commonly used because of its low price. There are other kinds of acids commonly used, however, such as muriatic (hydrochloric), nitric, and hydrofluoric, each of which has its particular use. If a combination action is desired, such as pickling with a slight etch effect, for example, prior to galvanizing or tinning, a solution of muriatic or muriatic and sulfuric will give the desired result. Muriatic acid will pickle relatively faster and with greater safety against pitting than sulfuric, but its higher cost prevents its general use. Muriatic, either straight or in combination with other acids, is used in the pickling of castings and for chrome and stainless steels where it is necessary to remove heavy and tight coatings of scale and where, along with other factors, sulfuric acid would be unsuitable. Nitric acid is used in electrolytic pickling to passivate the surface of stainless steels and occasionally to oxidize scaled surfaces to facilitate pickling. Hydrofluoric acid is used to accelerate the pickling acid in the bath, such as in the primary pickling of high chrome or chrome-nickel stainless steels and occasionally in pickling castings for the removal of sand.

Acid Concentration.—The acid concentration of the pickling bath is of the utmost importance. The proper concentration will depend upon a number of variables such as the kind of acid employed, the nature of the material to be pickled, the temperature of the bath, and the time available for pickling.

The activity of a sulfuric acid pickling bath is approximately in direct proportion to the acid concentration up to about 25 per cent of acid by weight. Increase in acid concentration above

this amount will cause a relative decrease in the activity of the bath. By varying the acid percentage, the activity of the pickling bath can be increased or decreased within wide limits. The percentage of acid that produces the best result on pickling carbon steels or pearlitic alloy steels ranges from 5 to 10 per cent. Both nitric acid and muriatic acid are used in concentrations ranging from 5 to 50 per cent by volume.

Some form of vigorous agitation is desirable during pickling so as to secure uniform acid concentration throughout the bath. Agitation not only aids uniform pickling through equalizing acid concentrations but also eliminates the tendency of gas pocket formation around the work as will occur when pickling in a stagnant bath. Gas pockets would keep the acid from the metal and arrest the action in these localized areas.

The acid concentration of the bath should be maintained at all times above the minimum amount necessary for pickling the material. The concentration should be frequently checked by chemical analysis. The use of a hydrometer is not recommended for the checking of the solution because of the gravity variations introduced by the ferrous sulfate which is the result of the reaction between scale or iron and sulfuric acid.

Pickling Temperature.—One of the most rapid ways of increasing the rate of any pickling operation is to raise the temperature of the bath. It is found that sulfuric acid at 190°F. has a solution rate 100 times greater than its rate at room temperature. For short-time cycles, temperatures between 170 and 190°F. are found to be generally satisfactory. On some steels, such as many high carbon and alloy steels, temperatures of between 140 to 150°F. are more satisfactory.

Certain precautions should be observed in using relatively high temperatures, such as overpickling, establishing a limiting temperature when using an inhibitor as many inhibitors will fail at relatively high temperatures, and controlling the temperature of the work leaving the bath, as a high temperature of the work will cause complete evaporation of the adhering film of pickling solution before the work reaches the rinse tank and the resultant oxidation will appear as brown spots or stains on the surface.

The oxides usually considered in the pickling of iron and steel are of three common varieties: the ferric oxide, Fe_2O_3, which contains the most oxygen; Fe_3O_4 is the next; and FeO, ferrous

oxide, is the leanest and the closest to the metal. FeO is the most difficult of the oxides to dissolve which explains the difficulty often encountered on pickling heat-treated bars. FeO, however, upon slow cooling will disintegrate around 1100°F. (590°C.) into Fe and Fe_3O_4. This mixture is very much more soluble than either Fe_3O_4 or Fe_2O_3 alone. The old theory of pickling was that the steel pickled away from under the scale. A study of the reactions involved, combined with the above knowledge of the characteristics of the oxides, will account for this apparent pickling of the scale on the underside.

$$Fe + H_2SO_4 = FeSO_4 + H_2 \quad (1)$$
$$FeO + H_2SO_4 = FeSO_4 + H_2O \quad (2)$$
$$Fe_3O_4 + 3H_2SO_4 + H_2 = 3FeSO_4 + 4H_2O \quad (3)$$
$$Fe_2O_3 + 3H_2SO_4 + H_2 = 2FeSO_4 + 4H_2O \quad (4)$$

In the equation (1) where iron is being pickled, the products are ferrous sulfate with hydrogen. In (2) the by-product is water and no hydrogen. In (3) and (4) no hydrogen, but hydrogen is being absorbed on the left side of the equation to reduce the higher oxides.

From these reactions which are involved in the pickling process, we can conclude that when hydrogen bubbles to the top of the bath, metal is being attacked. When scale is dissolved, water is being formed and not hydrogen.

Electrolytic Theory of Pickling.[1]—Between any two different materials in an acid bath there is an electromotive force or a voltage generated. If these parts are short-circuited to each other, as they are when welded into the same piece of steel, there is a flow of current between the two different materials, setting up an electrolysis and corrosion. A hot acid solution is an excellent electrolyte; therefore, if scale and iron are welded to each other and exposed to the hot acid solution, an electrolysis will result with scale as one pole and iron as the other. The iron is the positive pole or anode, while the scale is the negative or cathode (see Fig. 22-XI).

Since current takes the shortest course, the electrolysis is between the underside of the scale and the steel, not the top side. It starts at some crack or opening in the scale where the acid solution can enter. This explains why the impression is obtained

[1] Taken, by permission, from *Metal Cleaning Finishing*, June, 1937.

that hydrogen is being generated under the scale and actually pushes it off. The electrolysis is working wherever the acid solution can penetrate between the scale and the iron. A certain amount of hydrogen is being generated in this crevice and some of the acid acts on the iron momentarily. Therefore, a slight bubbling action of hydrogen is seen coming to the surface when a fresh piece of steel has been immersed in an acid solution, even though that acid solution may be inhibited.

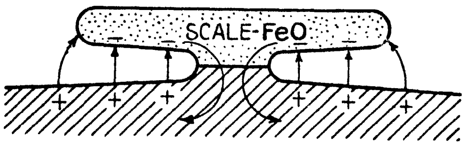


FIG. 22-XI.

As the solution of the bond between the scale and the iron is finally completed, the piece of scale drops off and falls to the bottom of the tank. From here on, the solution of iron oxide in a sulfuric acid bath is fairly slow, as is evidenced by the presence of scale in the residue at the bottom of a pickling tank when the tank is dumped. While the scale is attached, the solution is accelerated by the electrolytic pressure varying from approx-

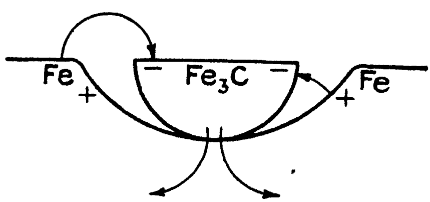


FIG. 23-XI.

imately ½ to 1½ volts, while thereafter it is straight chemical solution.

Between any other two constituents of the steel there is also a definite potential difference. Impurities like sulfides and phosphides, alloys, chrome carbides and nickel, all have definite potentials in relation to one another and in relation to iron.

The carbon in steel is present as iron carbide, Fe_3C, or cementite. There is a potential difference between iron carbides and iron, in which the iron is the anode, or positive, and the carbide is the cathode, or negative. The acid in this case attacks the iron, leaving the cathode untouched (see Fig. 23-XI).

The iron area immediately surrounding a cementite particle is dissolved until the cementite particle is entirely free. The iron dissolving leaves a pit, while the cementite or carbide sets itself on the surface as a smut. We note that the higher the carbon content of the steel, the more violent is the pickling; therefore also the more numerous the reactions.

The solution of the steel under the scale is only momentary and does no real damage to the steel surface but, where the cementite is located, the solution of the iron surrounding the cementite particle goes on and does the real damage as to pitting. Inhibitors are used to diminish the attack of this second reaction.

Inhibitors.—The definition of an inhibitor according to the 1939 edition of the A. S. M. Handbook is: "Pickling inhibitors are agents which may be added to an acid pickling bath to diminish the attack of the acid on the metal areas from which the scale has been removed, without appreciably retarding the rate of scale or rust removal by the acid, and to diminish the severity of hydrogen embrittlement."

The theories regarding the mechanism of inhibitor action have been under considerable discussion. It is known that inhibitors save steel and acid but the exact reasons are not well understood. Various theories have been advanced, several of which in brief are: The electrolytic theory which postulates the adsorption or plating out of a very thin layer of inhibitor material on the surface of the metal, thereby preventing any further electrolytic action between the surface of the material and the acid pickling bath. Other investigators have postulated the belief that the inhibitor acts as a negative catalyst that is selective in its action, retarding the action of the acid on the metal but not on scale. Others have stated that the inhibitor action seems to be associated with an increase of hydrogen overvoltage at the metal surfaces. A protective coating of hydrogen is thereby maintained at the surface and protects the metal from direct contact with the acid and retards the action.

The range of inhibitors is wide and includes such materials as wheat bran or offgrade flour, sludge acid from oil refineries, waste animal materials, gelatin, and various sulfur and nitrogen-containing chemicals. The effectiveness and uniformity of inhibiting by these various materials vary widely.

The advantages and disadvantages of acid inhibition are

Advantages:

1. It produces a reduction of metal loss and saves pickling acid.
2. It prevents or minimizes the scrap losses due to overpickling or pitting.
3. It decreases the effect of blistering and hydrogen embrittlement.

Disadvantages:

1. It increases pickling time.
2. It has the possibility of leaving an objectionable surface film which may interfere with subsequent operations.
3. It adds to the cost of pickling.

Pickling Defects.—Certain defects that make their appearance upon pickling are often blamed upon improper operation of the pickling cycle or upon faulty steel. Many of these, however, are not due to these causes but are the results of previous operations, such as rolling, forging, or heat-treating. Some of the main defects associated with pickling are as follows:

Overpickling.—Overpickling is the result of holding the material in the pickle bath over the time required for optimum results. The effect is a loss of weight and size of the material along with the presence of porosity and roughening of the entire surface.

Pickle Pitting—This type of pitting is due to localized electrolytic action between the scale and the clean metal and occurs only when the scale has been removed from small areas prior to pickling. It is characterized by a patchwork of pitted areas of irregular shape which frequently are aligned in a longitudinal direction on the material. The pits are usually sharply defined; uniform in depth with an inhibited bath and irregular in depth with an uninhibited bath.

Pits are also found to be caused by overpickling, although this rarely occurs. They may also have their origin in the rolling process because of the rolled-in scale or refractories at which points the pickling action is intensified.

Hydrogen Embrittlement.—This particular phenomenon is one which is not usually evident. It gives trouble usually when cold-working operations have followed too soon after pickling. It apparently is due to the diffusion of atomic hydrogen into the metal. When hydrogen ions are evolved at the exposed surface of the metal due to the direct acid attack, not all the resulting

nascent hydrogen links together to form molecules to appear as gas bubbles; some diffuses into the steel. This type of embrittlement is not permanent and may be removed by aging for a few days at room temperature or removed more rapidly by soaking in boiling water. Inhibitors also aid in minimizing this effect.

Blisters.—This type of defect is a troublesome one which occurs on sheet and strip steel. There have been several theories advanced as to their cause, the most tenable one being as follows: It is necessary that there be present in the sheet lamellar or plate-like nonmetallic inclusions or cavities in which there is present amorphous iron produced by the reduction of ferrous oxide. During pickling, hydrogen, which is absorbed by the steel, diffuses into these inclusions and cavities and is catalytically converted by the amorphous iron into molecular hydrogen. The gas thus formed cannot escape and eventually builds up a pressure which is sufficient to rupture the steel along the planes of weakness produced by the inclusions. This view is confirmed by the observed facts that blisters never occur in thoroughly killed steels because the inclusions, even though they may be numerous, do not contain free ferrous oxide. They seldom occur in strongly oxidized steels, because the strong rimming action has almost completely cleansed the steel of blister inclusions. In addition, if the sheets are not pickled, blisters will not occur.

Rolling Defects.—The defects found in rolled steel products are a continual source of expense to the manufacturer. Good operating practice and rigid inspection will minimize the amount of defective material that leaves the plant. In most cases, thorough inspection will detect the defects but there are some of an internal character which are apt to escape the inspector and be present in the finished product. The defects discussed here are those found in blooms and billets but they are common to all semi-finished products, such as slabs, skelp, sheet bar, and also to finished products.

The defects commonly met with are due to one or more of the following five causes: (1) scaling, (2) temperature effects, (3) shearing, (4) the steel itself, and (5) the rolling operation. Of these, those caused by incorrect temperature adjustment, incorrect or careless shearing, and poor mill operation can be corrected and eliminated in the rolling mill itself. Defects due to the steel itself can be largely corrected in the steelmaking

division through better furnace and teeming practice. Scaling during the rolling operation cannot be eliminated but it can be minimized, as well as the defects caused by it, by careful manipulation of the steel in the mill.

A *rough* or *pitted surface* is due to scaling of the steel during rolling or reheating. Part of this effect is due to the rolling of scale into the surface but the deep pits have their origin in near-surface blowholes which have opened up and oxidized. The oxide formed in these pits becomes so deeply imbedded in the metal that pickling will not remove it and the oxide must be chipped out. Rough surfaces can be largely eliminated by proper removal of the scale during rolling and by correcting the pouring procedure to eliminate blowholes near the surface. In the case of some alloy steels, particularly nickel steels, the scale is so adherent that it is very difficult to remove it during rolling. This defect is, therefore, quite difficult to eliminate entirely.

Slivers are small pieces of metal that have become embedded in the surface and are elongated by the rolling operation. They can usually be traced to improper teeming (causing splashing) or to tearing of the edges of the piece during rolling. Tearing of the metal is believed to be due to many things, such as burning, twisting in the rolls, and improperly adjusted guides.

Scabs are formed when scale is rolled into the surface of the metal. The cause of this defect is difficult to eliminate entirely. They can be minimized by keeping the surface of the piece as free from scale as possible during rolling.

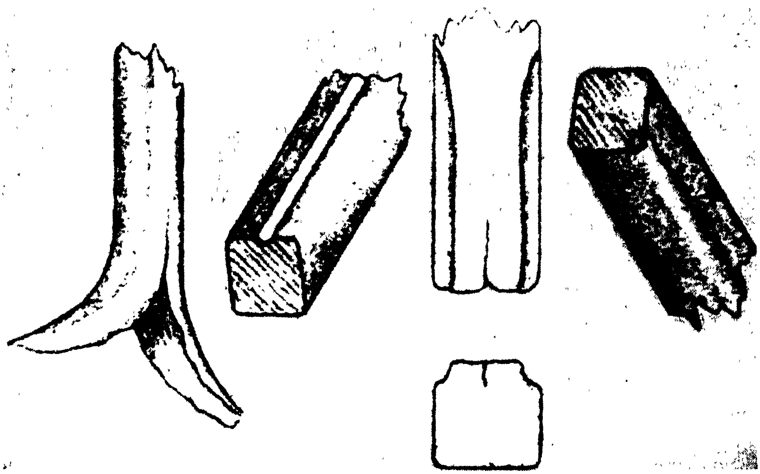
A *lap* is caused by overfilling the pass, causing the steel to spread out between the collars of the rolls. When the steel is turned for the next pass, this projection is rolled into the surface and the space between the lap and the rest of the surface is left as a surface crack (Fig. 24-XI *D*).

Seams are often caused by blowholes, laps, or tearing of the steel. If slivers or scale is rolled into the surface and then torn loose, the cracks left often elongate into seams with continued rolling. They may also be caused by not turning the bloom often enough during rolling.

Cobbling is one of the most frequent mill failures. It occurs as a twisting of the piece in the rolls in the blooming mill and occurs when the piece catches on a guide or roller, or is fed too rapidly to the rolls. In any case, the piece buckles more or less badly

and part or all of it must be scrapped, although uninjured parts can be sheared out and used.

Collar marks are caused by the roll collars biting into or otherwise marking the steel being rolled. Overfilling the pass or poor alignment of the rolls will cause the piece to twist and the collars to bite into it. The deep cuts caused by this can seldom be rolled out and the injured portions must be scrapped (Fig. 24-XI *C*).



A *B* *C* *D*

FIG. 24-XI.—*A*, fish tail; *B*, split head; *C*, collar mark; *D*, lap. (*Courtesy of C. R. Lynch.*)

Guide marks are caused by improperly adjusted guides or ones required to do too heavy duty. This will score the surface of the steel, leaving fine lines on the surface, or will tear the edges of the piece (Fig. 24-XI *B*).

Ragging marks are protrusions on the surface of the metal caused by contact with "ragged" rolls. These protrusions, if the rolls are improperly ragged, will be rolled into seams or laps. The smaller the size of the finished product or the smoother the desired finish on the product, the lighter must be the ragging on the roughing rolls.

Shearing Defects.—If the bloom is not cropped back sufficiently at the bloom shear in order to remove the pipe completely, rejection of the billet may result from this defect. A dull shear knife will fail to cut cleanly and will leave a lip where the

stroke ends. Mechanical pipe caused by fishtailing (split ends), due to mushy or porous tops and ingots that are uneven in temperature, must also be removed or rolled with extreme care to prevent internal defects or continued splitting well into the bar (Fig. 24-XI *A*). A small pipe is caused by the shear as it cuts through the metal because it tends to pull metal out of the center, leaving a cupped end. This is caused by segregated centers, spongy centers, or incorrect temperature during shearing. The cupped end may be folded together and rolled out with continued rolling to form internal seams.

Cracks are often formed at the blooming mill if too heavy a draft is taken or if the metal does not yield properly. These cracks are sometimes several inches in depth and, after becoming oxidized, are closed up but not welded by further rolling. After new scale forms over them, these internal seams cannot be seen on the surface and become a serious source of weakness in the finished product. The tendency to crack is sometimes blamed upon red shortness of the steel or upon careless handling at the blooming mill. Alloy steels should be treated very carefully during rolling as they are more apt to crack than plain carbon steel of the same carbon content, the latter being more plastic. Uneven heating in the soaking pit will also account for cracks appearing in the cooler portions.

Suggested Questions for Study and Class Discussion

1. What is the difference between an open and a closed pass? Illustrate by sketches.

2. Compare reversing and three-high blooming mills as to construction, operation, and economy.

3. List and compare the different types of billet mills.

4. Compare sheared and universal plate mills.

5. Describe the operation of rolling a 1¾- by 1¾-in. billet from an 18- by 22-in. ingot. Make the description as complete as possible.

6. List and discuss briefly the defects commonly encountered in rolling blooms and billets.

7. Give the various precautions that should be observed in general reheating operations. Compare batch and continuous reheating furnaces.

8. What particular precautions are necessary in order to roll stainless steel plate successfully?

9. Define the term "merchant mill." Describe one type of merchant mill.

CHAPTER XII

THE MANUFACTURE OF STEEL STRIPS, SHEET, AND COATED PRODUCTS

Prior to the introduction of the continuous wide strip mill within the past few years, a sharp distinction existed between sheet and strip. Sheet was produced from sheet bar by pack rolling in two-high mills and the length of the sheet rarely exceeded 12 ft. Strip, on the other hand, was produced in long lengths and relatively narrow widths in coil form. In modern practice, however, the increased accuracy of the strip mills has permitted the rolling of wider sheets, so that the older specified differences between sheet and strip based on widths have become arbitrary figures.

Strip in addition to these technical classifications is a term used in the industry to describe the long flat-rolled material as it comes from the rolls, either straight or in coils before it is cut into sheet sizes. Cold-rolled material in coils is also generally referred to as strip although it may later be sheared into sheets of various finishes. Sheet steel, as the name implies, consists of steel in the form of flat pieces that are both relatively thin and wide.

Another important distinction between sheets (strip) and plates lies in the surface finish and their application. With the exception of stainless plates, utility is the prime consideration in the application and, hence, little regard is paid to surface finish except insofar as the surface defects might impair the strength or ductility of the material. On the other hand, sheet steel is required to have a good surface finish in all cases. The finish is often the most important requirement.

Steel.—The steel used in the rolling processes to be described is made in either the acid Bessemer, basic open-hearth, or electric furnace and may be of either the killed, semikilled, or rimmed types. In recent practice the tendency is toward an increasing use of rimmed steel. The main reason for this preference is that rimmed steel is clean, with few inclusions such as silica and

alumina, often found in killed steel. Another advantage is less shrinkage with an increased yield as compared to the killed steels. However, with the developments in melting practices, many of the disadvantages in both types have been eliminated to a large extent.

The following two tables, taken from the specifications as issued by the Association of Steel Manufacturers Technical Committee, 1938, show the technical differences between flat-rolled carbon steel products.

STANDARD CLASSIFICATION BY SIZE OF FLAT-ROLLED CARBON STEEL

Hot-rolled

Width, in.	Thickness, in.						
	0.2500 or thicker	0.2499–0.1875	0.1874–0.0568	0.0567–0.0344	0.0343–0.0255	0.0254–0.0142	0.0141 or thinner
Up to 3½	Bar	Strip	Strip	Strip	Strip	Sheet	Sheet
Over 3½–6	Bar	Strip	Strip	Strip	Sheet	Sheet	Sheet
Over 6–12	Plate	Strip	Strip	Sheet	Sheet	Sheet	Sheet
Over 12–32	Plate	Sheet	Sheet	Sheet	Sheet	Sheet	T. M. black
Over 32–48	Plate	Sheet	Sheet	Sheet	Sheet	Sheet	Sheet
Over 48	Plate	Plate	Sheet	Sheet	Sheet	Sheet	

Cold-rolled

Widths, in.	Thickness, in.		
	0.2500 or thicker	0.2499–0.0142	0.0141 or thinner
Up to 12	Bar	Strip	Strip
Over 12–24	Strip*	Strip*	Strip
Over 12–24	Sheet†	Sheet†	T. M. black
Over 24–32	Sheet	Sheet	T. M. black
Over 32	Sheet	Sheet	Sheet

* When a definite temper as defined in A.S.T.M. specification A-109, or a special edge, or special finish is specified.

† When no special temper, edge, or finish is specified.

The chemical composition of most of the steel used in making the products to be studied conforms to the following general specifications: 0.04 to 0.12 per cent carbon, from 0.30 to 0.50 per

cent manganese, about 0.08 per cent phosphorus for pack rolling (0.10 per cent for acid Bessemer steel), or less than 0.015 for cold rolling, and from 0.03 to 0.05 per cent sulfur.

When sheet is hot-rolled to its final thickness by the conventional method of pack-rolling or doubling the sheets repeatedly, it is usually considered essential that a small amount of phosphorus be present to prevent the sheet from sticking together. In continuous cold rolling of steel without doubling of the sheet, there is no need for preventing sticking and hence the phosphorus is kept low. This elimination of phosphorus has been considered, in part at least, to be the factor in the improved ductility and formability of cold-rolled steel.

Gauge.—In the metal trades the word gauge is used loosely as a synonym for thickness when applied to sheet or strip material. When correctly used, however, it is used in connection with various systems, or scales, for expressing the thickness or weight per unit area of thin plate, sheet, strip, tin and terne plate, or the diameter of rod and wire. Several gauge standards have been introduced and, because they are not alike, considerable confusion has often arisen between the manufacturer and the user. In most cases, however, uncoated steel sheet thicknesses are designated by gauge numbers according to the United States Standard Gage (U.S.S.G.). Light plates also fall within the limits of this classification. Material heavier than that included in Table 1-XII is described by giving the weight in pounds per square foot or the thickness in ordinary units. The diameters of steel wires corresponding to the various gauge numbers are also included in the table. This gauge system is used for all steel wire, except music wire, and is known as the Steel Wire Gage (Stl.W.G.), or the United States Steel Wire Gage (U.S. Stl.W.G.).

Sheet Steel Production.—The manufacture of steel sheets is so large a subject that it cannot be covered adequately in the space available and only a brief résumé will be undertaken. The older pack-rolling method will be considered first and will be followed by a brief summary of the recent mechanical improvements that have been installed in some sheet mills to increase the tonnage and decrease the crew necessary for their operation. The newer continuous methods of rolling sheet and strip will be considered next, followed by a brief discussion of the produc-

TABLE 1-XII.—SHEET AND WIRE GAUGES

U.S. Standard Gauge (U.S.S.G.)			Steel Wire Gauge (U.S.Stl.W.G.) (Stl.W.G.)
Gauge No.	Equivalent thickness, in.	Lb. per sq. ft.	Thickness, in.
7/0's	0.4902	20.0000	0.4900
6/0's	0.4596	18.7500	0.4615
5/0's	0.4289	17.5000	0.4305
4/0's	0.3983	16.2500	0.3938
3/0's	0.3676	15.0000	0.3625
2/0's	0.3370	13.7500	0.3310
0	0.3064	12.5000	0.3065
1	0.2757	11.2500	0.2830
2	0.2604	10.6250	0.2625
3	0.2451	10.0000	0.2437
4	0.2298	9.3750	0.2253
5	0.2145	8.7500	0.2070
6	0.1991	8.1250	0.1920
7	0.1838	7.5000	0.1770
8	0.1685	6.8750	0.1620
9	0.1532	6.2500	0.1483
10	0.1379	5.6250	0.1350
11	0.1225	5.0000	0.1205
12	0.1072	4.3750	0.1055
13	0.0919	3.7500	0.0915
14	0.0766	3.1250	0.0800
15	0.0689	2.8125	0.0720
16	0.0613	2.5000	0.0625
17	0.0551	2.2500	0.0540
18	0.0490	2.0000	0.0475
19	0.0429	1.7500	0.0410
20	0.0368	1.5000	0.0348
21	0.0337	1.3750	0.0317
22	0.0306	1.2500	0.0286
23	0.0276	1.1250	0.0258
24	0.0245	1.0000	0.0230
25	0.0214	0.8750	0.0204
26	0.0184	0.7500	0.0181
27	0.0169	0.6875	0.0173
28	0.0153	0.6250	0.0162
29	0.0138	0.5625	0.0150
30	0.0123	0.5000	0.0140
31	0.0107	0.4375	0.0132
32	0.0100	0.4062	0.0128
33	0.0092	0.3750	0.0118
34	0.0084	0.3437	0.0104
35	0.0077	0.3125	0.0095
36	0.0069	0.2812	0.0090
37	0.0065	0.2656	0.0085
38	0.0061	0.2500	0.0080
39	0.0057	0.2344	0.0075
40	0.0054	0.2187	0.0070
41	0.0052	0.2109	0.0066
42	0.0050	0.2031	0.0062
43	0.0048	0.1953	0.0060
44	0.0046	0.1875	0.0058

tion of stainless steel sheets. The protective coatings applied to sheet steel for special applications will be studied along with the methods of application.

The first step in the manufacture of sheet by the pack-rolling method consists in rolling the bloom into sheet bar. For many years sheet bar was produced in one standard width of 8 in. and of varying thickness to give weights ranging from 7 to about 60 lb. per linear foot. Owing to the present-day requirements for long sheets, however, some mills are equipped to roll sheet bar wider than 8 in. The bloom (usually 4 by 6 in.) is roughed down in tongue-and-groove passes in all but the last one or two passes where plain chilled rolls are used to produce a good finish on the material. Edging stands are generally used in continuous mills. Jets of high-pressure water play on both sides of the bar before and after entering the finishing passes in order to remove the scale.

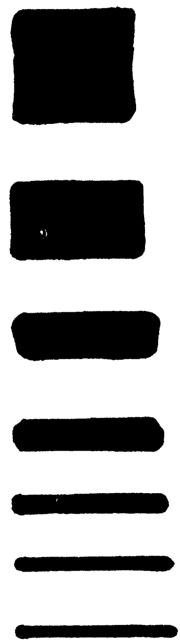


Fig. 1-XII.—Reductions used in obtaining sheet bar from a bloom in six passes.

One type of mill for rolling sheet bar is a two-high reversing mill with a number of grooves cut in the rolls to produce the required number of passes, usually six in number. The actual number of times the bar is passed through the rolls depends upon the temperature of the bar, as the early reductions are rather severe. The bar is usually turned over when shifting from one groove to another. The shape of the bloom and of the piece after finishing in each groove is shown in Fig. 1-XII. Instead of having all the grooves cut in one roll, two parallel trains of rolls may be used, each train being composed of three stands in most cases. One pass is cut in each stand of rolls and the piece is rolled in one stand before being passed to the next. This type of mill is often more satisfactory than a single stand of rolls.

With the rapid increase in demand for steel sheets, the continuous sheet-bar rolling mill was developed because it was able to produce a much higher tonnage of sheet bar at a lower cost. One such mill[1] is composed of ten horizontal and three

[1] Fiske, R. A., *Iron Age*, **121**, 799 (Mar. 22, 1928).

edging stands arranged in tandem, the stands being about 12 ft. apart. The first three stands comprise the roughing set and contain 24-in. diameter horizontal rolls, all being gear-driven from a 3,600 hp. variable speed motor. Following the third stand is placed a separately driven 18-in. edging stand. The intermediate set immediately follows the roughing set and is composed of four 21-in. diameter horizontal stands and a 16-in. edging stand, the edging stand being placed with two horizontal stands on either side of it. All five stands are gear-driven by a 6,500 hp. motor. Immediately after the intermediate set is situated a third edging stand of 16-in. rolls but separately driven by an electric motor. The three finishing stands are composed of 21-in. diameter rolls and are separately driven by three 2,000-hp. variable-speed motors. A cropping shear is provided at the entering end of the mill and both a steam flying shear and a rotary shear at the delivery end. A runout table leads to an automatic bar piler and cooling beds. The sheet bars can be water-quenched on the runout table by enclosed sprays if desired. Hydraulically operated loopers are provided to loop the sheet bar between the stands where slack occurs.

Regardless of the type of mill used, the sheet bar is almost always rolled on the original heat of the ingot, the blooming mill feeding blooms directly to the sheet bar mill. The mill being set up for sheet bar, different thicknesses can be obtained by merely operating the screw-downs. In rolling, the surface and gauge of the bar are watched with particular care since the size and finish of the sheet produced from the bar are dependent upon these factors to a considerable degree. Sheet bar falls heir to most of the defects encountered in other semifinished products, the most important of these being seams, blisters, cobbles, rough surface, and unequal draft on both sides of the bar. In shearing the sheet bar, care should be taken to ensure that no burr or lip is left on the end of the bar by the shear. The bar must have a clean-cut edge or it will mark the hot rolls. The sheet bar is usually cut into lengths of about 30 ft. by the flying shear.

The cooled and inspected sheet bar is conveyed to the sheet mill where it is cut to the required length in a sheet bar shear. The sheet bar is cut to a length slightly longer than the width

of the sheet to be rolled from it since the sheet bar is cross-rolled to produce the required length of sheet. The thickness of the sheet bar is, therefore, adjusted to produce the desired thickness of sheet when the bar has been rolled out to the required length. The extra length of the sheet bar as cut is designed to allow for shearing the sides of the sheet to the required width. The modern bar shear is designed to adjust and accurately cut several bars at once.

The method of producing sheets by pack rolling consists essentially in heating the bars to a rolling temperature, elongating them to about half their final length in a roughing mill, and matching about three roughed sheets of the same size. The matched sheets are piled one upon the other, reheated, and finished to the required gage as a pack, all of them being rolled at once as a unit. In producing very thin sheets, the matched sheets are doubled and finished as a doubled pack. The sheets coming from the finished rolls are known as *black sheets.* The method to be described is one that has been in use for many years and the general method is still very widely used. The relatively recent changes from the methods to be described have been mainly in the mechanical details rather than in rolling principles. These improvements will be considered subsequently.

The hot mills—a roughing and a finishing stand—are two-high nonreversing mills and are placed side by side. In large installations, several sets of roughing and finishing stands are placed in train and driven by a single motor placed in the center of the train. Roughing and finishing stands are placed alternately and a flywheel is included in the train—usually next to the motor—to prevent the mill from stalling on peak loads. Ten stands can be satisfactorily coupled in this manner and driven by a single motor geared down to 30 to 40 r.p.m. In some sheet mills, only the bottom roll is driven, the top roll being loose in its bearings and rotated by frictional contact with either the sheet or the bottom roll.

The roughing stand contains two plain, smooth-surfaced rolls of equal diameters set in heavy housings of the closed top type. The rolls are of cast iron and may or may not be chilled (discarded finishing rolls are sometimes used), the size of which varies with the width of the sheet being rolled. The rolls must be about 6 in. longer in the body than the widest sheet to be

rolled on that stand and, as the lengths of the rolls are increased, their diameters must also be increased to maintain stiffness. In most cases, the rolls vary in size from 22 to 32 in. in diameter and from 30 to 60 in. long in the body. Some mills are equipped with rolls 72 in. in length in order to compete with wide continuous sheet. The roll necks for the bottom roll are set in heavy bearings while driving spindles and couplings connect the bottom rolls on adjacent stands of the train. The

FIG. 2-XII.—A ten-stand continuous-sheet-bar mill in operation. (*Courtesy of The Youngstown Sheet & Tube Co.*)

heaviest parts of the bearings for the top roll are at the top where the most pressure comes. Either a motor-driven or a hand-operated screw-down is provided and is so arranged that the screws that extend vertically through the top of either housing are turned the same amount, thus keeping the rolls parallel. When the mill is running idle, however, the top roll is not in contact with the screws but, when a bar is fed into the rolls, it jumps up from its former position in contact with the bottom roll in order to allow the passage of the bar. The screws limit the rise of the top roll, the maximum rise being about ⅝ in. in

most roughing stands. After the material has passed through the rolls, the top roll falls down again upon the bottom roll. This type of mill is known as a *jump mill* for obvious reasons, and the roughing stand is known variously as a *soft mill*, a *break-down mill*, and a *roughing mill.*

The jump mill cannot be applied to roughing very heavy bars because the shock produced by the jumping of the top roll

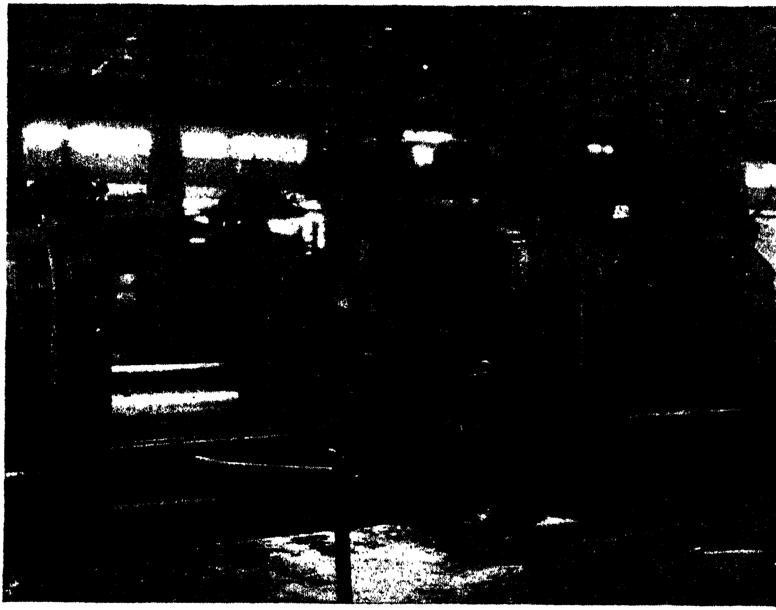


FIG. 3-XII.—A two-stand sheet mill from the catcher's side. Balanced break-down stand at right, finishing stand at left. (*Courtesy of The United Engineering & Foundry Co.*)

through distances greater than about ⅝ in. is very destructive to the mill. In these cases, a balanced type of roughing mill is used in which the top roll is kept up against the screws at all times, usually by the use of springs. Since the top roll is not in contact with the bottom roll when running idle, means must be provided for driving this roll at the same speed as the bottom one. This is usually accomplished by either a chain or gear drive from the bottom roll or an auxiliary motor drive. The jump type of mill is simple and economical to operate and is usually used when it is possible to do so.

The finishing stand is of the jump type but has a maximum rise of the top roll of ¼ in. or less. The screw-downs are operated by levers extending down from the tops of the housings within easy reach of the roller and are connected by a bar so that the same amount of pressure can be exerted through both screws. The levers are swung through about a 90-deg. angle to reduce the distance from ¼ in. to practically zero. The rolls are always of highly polished, chilled cast iron with a depth of chill of about 1 in. to allow for redressing several times before wearing through the chill. The finishing mill is always run dry and the rolls get hot through contact with the sheets passing between them. Since the rolls get hotter at their centers where the most work is done, they are usually dressed slightly concave in shape so that the greater expansion at the center will swell the rolls just enough to produce true cylinders. The rolls used to be warmed up prior to rolling sheets by rolling narrow widths of iron for about eight hours. At present, however, the rolls are usually warmed by running them idle with carefully adjusted gas burners playing on them. In this way the rolls may be warmed more rapidly and evenly than by the old method. With continued rolling, the centers of the rolls are apt to expand too much, in which case they are usually cooled with dry steam. Two pipes are provided running the length of the rolls on the catcher's side of the mill and perforated to direct the steam on the rolls. More steam is directed at the center of the rolls where it is most needed than at the ends. The temperature of the breakdown rolls is controlled in the same manner if they are run dry. In some cases, however, the roughing rolls are kept cool by water, in which case wipers are used to keep the cooling water off the sheets being rolled and the rolls are dressed without any concavity. Finishing rolls, in general, run at about 450°F., and the breakdown rolls about 100°F. hotter if run dry. About once a week the rolls must be redressed as they lose their polish and also become hollow by being worn away more rapidly at their centers than at their ends.

The train of roll stands is usually placed lengthwise of the building and sunk in a narrow pit just wide enough to accommodate the housings. This is done in order to place the opening between the rolls at about the level of the mill crews' waists or a little lower, so that they may handle the sheets with the

most convenience. About 20 ft. from the rolls, a line of heating furnaces is placed parallel to the stands and along one wall of the building with their doors facing the stands of rolls. The floor space on the other side of the roll stands is left bare to accommodate the sheets while cooling, except for the shears on which the finished sheets are cut to size.

Two furnaces are provided for each pair of roll stands (roughing and finishing) and are called, respectively, the *pair* furnace and the *sheet* furnace, the former being placed directly behind the roughing stand and the latter behind the finishing stand. Both are usually of comparatively simple batch-type construction, being composed of a small combustion chamber separated by a low bridge wall from the larger square heating chamber in front. Gas or oil are the usual fuels. The heating chamber has a corrugated floor to allow the passage of the hot gases under the bars or sheets which are laid on the corrugations. The exit flues are usually at the front of the furnace to prevent air from being sucked in through the doors. As the material being heated must be kept free from scale, the fuel is burned with insufficient air in order to maintain a nonoxidizing atmosphere in the furnace (incomplete combustion).

The following description of the method of pack-rolling sheets is believed to be a typical example but differs in details from methods followed in some mills. The most important deviations will be pointed out in the description. From 20 to 40 sheet bars correctly sheared to size are charged into the pair furnace and laid up near the bridge wall at the back of the furnace until they are heated through to the required temperature. The temperature used ranges from 1250 to 1450°F., depending upon conditions. When the bars have reached the desired temperature, they are stacked near the front of the furnace in two or three piles for soaking until needed and another heat of bars is charged for heating. Two bars are withdrawn from the furnace at one time by the heater and placed on the "foreplate" where they are cleaned of scale or dirt with a steel brush. The screws are slacked off the desired amount and the rougher grasps one bar with his tongs and feeds it crosswise through the rolls. The catcher on the other side of the mill grasps the bar as it comes through and with the aid of a billyroll[1] raises the piece and passes it back over the

[1] The billyroll is a small diameter idler placed between the housings at the

top roll to the catcher. While the catcher is doing this, the rougher grasps the second bar, feeds it through, and then receives the first bar from the catcher who, in turn, receives the second bar as it emerges from the first roughing pass. The screw-down is then operated and the procedure repeated on both bars. Three to five passes are given to both bars in this manner, the screw-down being operated after each pass. The bars are thus gradually

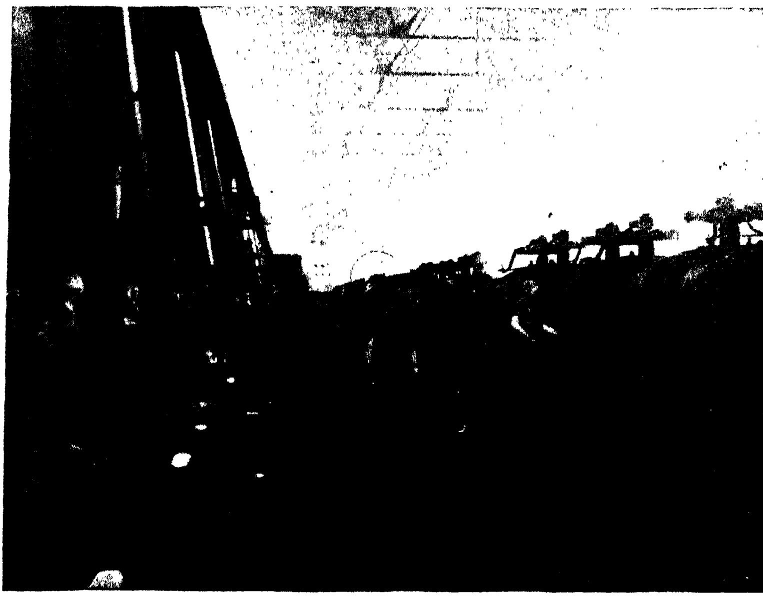


FIG. 4-XII.—View of a sheet mill in operation. (*Courtesy of The Youngstown Sheet & Tube Co.*)

reduced in thickness and increased in length. The partly broken down bars are then placed one on top of the other and given several passes matched together in this way, the screw-down being operated after each pass. Enough passes are given the matched pieces to elongate them to about one-half the desired final length of the sheets, the exact number depending on the desired final size and the temperature of the material. Two to four matched passes are usual, the final temperature being in

level of the opening between the rolls to help support the piece as it comes from the rolls.

the neighborhood of 1000°F. The two breakdowns are separated and allowed to cool and, in the case of high-grade sheets, automobile body sheets for example, are pickled to remove the scale and bring out any surface defects that may be present, such as scabs, seams, and blisters.

The method of hot-finishing the sheets depends to a large extent upon the gauge of the sheet that is being rolled. The breakdown sheets, after pickling, are carried to the sheet furnace and matched into piles known as packs. Sheets of nearly the same area and shape are placed in the same pack (matched), the idea being to produce packs of uniform size for rolling. The heavier gauges, 18 gauge and heavier, are matched two in a pack; 19, 20, 21, and 22 gauge are matched three in a pack; and 22 gauge in small sizes and finer sizes up to about 27 gauge, four in a pack. Finer gauges than these are produced by matching three or four breakdown sheets and doubling them over to produce a pack of six or eight sheets. In some cases, six and eight breakdown sheets are matched and finished without doubling, particularly in the better grades.

In any event, the packs are placed at the rear of the sheet furnace and heated to 1300 to 1400°F. and then pulled out to the front of the furnace for soaking until needed. Care should be taken by the heater to see that the sheet is heated evenly to the correct temperature. When ready, the pack is pulled from the furnace to the foreplate where the dirt is carefully brushed from it. The roller pulls the sheets apart, if they have stuck together during heating, in order to adjust the pack for final rolling. From three to five passes are required to finish the pack to the desired length plus an allowance for end scrap, the actual number depending upon the draft in each pass and the initial temperature of the pack. The length of the pack is gauged with a steel rod at intervals, as the length is the only means of determining the thickness of the sheets. Owing to the length and general unwieldiness of the long pack, the catcher must have some sort of mechanical contrivance to help him in passing the pack back over the rolls. This usually takes the form of two straight steel legs 40 to 50 in. apart (depending on the length of the rolls) and 6 to 8 ft. long. These legs are elevated a foot or more above the floor, extend back from the rolls parallel to each other, and are hinged at their centers. As the sheets come

through the rolls, they move out on the legs, and the catcher, by bearing down on the end farthest from the rolls, elevates the ends of the legs and the pack nearest the rolls and with a push starts them back over the top roll. A single leg in the center is sometimes used for this purpose and can be seen in Fig. 3-XII. The finished black sheets are cooled on the delivery floor of the mill, sheared in a pack to the desired size, and separated from each other.

Quite a few defects in sheets originate in the hot mills and considerable care must be used in order to eliminate them. A *full pack* refers particularly to a convex shape of the back end of the breakdown sheets and is caused by the center of the sheet being elongated more than the edges, owing to a slight puffing of the rolls at the center. If the ends are concave, the condition is known as *hollow pack* and is due either to a hollow or concave mill or to an underheated bar with a cool center or to both. If a full pack is finished on a hollow mill, pinchers result. This defect takes the form of ridges running in from the edges of the sheet. Sheets in which this occurs are also known as *spreaders* or *squeezers*. *Floppers* are usually caused by finishing a hollow pack in a full or slightly convex pair of rolls. In this case, the heavy draft in the center causes the back end of the pack to flop up and down as it enters the rolls, leaving ridges in the pack. Marks or scratches of any kind on the surface may cause rejection of the sheet. Grease marks, caused by lubricating grease being rolled into the sheets, are almost impossible to remove.

The hot-rolled sheets nearly always require some further treatment before they are ready for use but, before turning to the finishing operations, the other methods in use for hot-rolling sheets will be considered, as the finishing operations are about the same for sheets rolled by any method. The recent changes in methods of pack-rolling sheets have been due mainly to the heavy demand for high-grade sheets in large sizes by the automotive industry and the advent of continuous rolling of wide sheets and subsequent cold rolling of this sheet in continuous mills. The owners of the old-style sheet mills were forced to improve their tonnage output and decrease costs in order to compete with the continuous mills and meet demands.

An important development has been the introduction of continuous pair and sheet furnaces with automatic delivery of heated

bars and packs at the will of the mill operator by pushing a button on the mill housing. Conveyers in the pair furnaces convey the bars through the furnace, the bars being either laid flat on the conveyer (Fig. 5-XII) or supported on fingers in nearly an upright position in order to heat them evenly. The packs are conveyed through the sheet furnace by supporting them above the furnace bottom in a horizontal position on fingers so

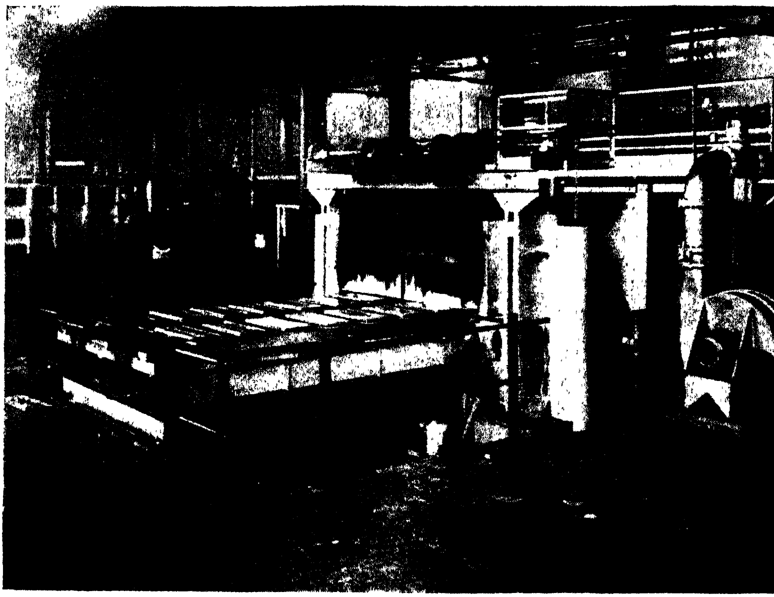


FIG. 5-XII.—Charging end of a continuous-pair furnace. (*Courtesy of The Youngstown Sheet & Tube Co.*)

that they may be heated evenly from both sides. In some cases where the breakdowns are roughed out on a second mill, both the bars and the breakdowns may be heated in the same furnace by having the two independently driven conveyers side by side.

Automatic front and back tilting tables have been installed on some of the two-high finishing mills in order to speed up production. On packs, the operation of the automatic tables in passing the pack back over the top roll is much faster than can be done by hand. The size of the mill crew is also cut down to two men. The limit is the amount of heat that the rolls can take,

as their temperature must be kept below about 700°F. Mechanical doublers have also been improved in design so that the pack can be more rapidly and accurately doubled for finishing to the finer gauges. Conveyer systems to and from the mill stands are also used to speed up the handling of the material and decrease the cost of handling. Automatic polishing equipment has recently been put into operation to polish the finishing rolls during operation. By proper control of the rate of travel of the polishing blocks back and forth across the face of the rolls, it is possible to keep the roll surfaces in shape, free from scale specks, and also keep the mill from becoming hollow too rapidly.

A recent design of three-high roughing stand is coming into use in some sheet mills. The top and bottom rolls are of the same size, but the middle roll is smaller. The bottom roll of this mill is driven by the mill engine while the top roll is turned by a pinion stand. The top and middle rolls are counterbalanced and the middle roll is actuated by the tilting of the back table. Automatic front and back tilting tables and an automatic matching device complete the mill setup. It is customary when roughing a pair of sheet bars on this type of mill to give each of them one pass through the bottom and a return pass through the top, match them automatically, and give the pair three more passes. The entire operation has been carried out in 20 sec. and seems likely to be reduced further. A simpler three-high mill is being used for roughing purposes and as an intermediate rolling mill. Only the bottom roll is driven and the middle roll jumps, as in sheared plate mill operation. These mills are usually run wet (sprayed with water) and are wiped to keep the water off the bars.

One type of mechanical pack-rolling mill consists of a two-high balanced roughing mill, a two-high jump-type run-over mill, and two two-high finishing mills in each unit. All stands are equipped with automatic tables and conveyer systems to and from the continuous heating furnaces. A single furnace is used for heating both sheet bars and run-over packs, while a continuous sheet furnace is placed behind each finishing mill. In operation, the sheet bar is given two or three passes in the balanced roughing stand and run to the matching table. One, two, three, or more sheet bars are given the same treatment, matched with the first bar, and returned in a pack to the furnace where they are

given a wash heat on the run-over conveyer. The pack is then released to the run-over stand where two or three more passes are taken. The pack is then doubled, if necessary, and charged into the sheet furnace for one of the two finishing mills. After heating, the pack is given the three to five finishing passes necessary to elongate it to the desired length and run along the runout table to be sheared after cooling. In some mills, a three-high stand is used to finish the breakdowns from the run-over stand in place of two two-high finishing stands. The three-high stand cannot be used to finish to thicknesses smaller than 22 gauge so a two-high finishing stand is provided to receive doubled packs of sheets and finish them to the finer gauges.

The finishing operations depend upon specifications and may include normalizing, annealing, pickling, cold rolling, "skin" or "temper" rolling, roller or stretcher leveling, followed by resquaring, oiling, or cutting to smaller size.

Continuous Hot Rolling of Narrow Strip.—The following discussion is fairly typical of narrow strip mill installations but the mills in different plants vary widely as to the methods of reduction, number of stands used, sizes of strip produced, and methods of driving.

For narrow strip the billet may be first reduced by alternate, oval, and square passes or by plain rolls with heavy edging stands set between the horizontal stands. For rather wide strip the intermediate reduction is sometimes carried out by a series of tongue-and-groove passes, each succeeding pair of rolls having a wider and shallower pass. In other cases where the width is at the desired value the reduction is continued on cylindrical rolls with edging stands to control the width. The last few stands are plain rolls in any case, in which the spreading of the strip is negligible. As might be expected, slabs are used as the starting point for the larger widths of strip and billets for the smaller widths.

The following layout[1] is a typical installation for rolling strip from ¾ to 6 in. wide and in minimum thicknesses of 0.025 in. for the narrow and 0.035 in. for the wider strip. The mill is equipped with two-high stands in which the rolls are true cylinders. Instead of the rolls having necks, roller bearings back up the rolls on the extension of the rolling surface and assure

[1] Fiske, R. A., *Iron Age*, **125**, 864 (Mar. 20, 1930).

ample bearing area and ruggedness of construction. Also the edging stands are of heavy construction in order that, when rolling narrow widths, they may be used for reduction of area by the insertion of vertical rolls with oval and square passes. The raw material used (billet) ranges from 1¾ in. square to 2 by 4¾ in. in section by 30 ft. long and is side-charged into a continuous heating furnace equipped with skids. The material travels sideways through the furnace, its direction of travel being at right angles to the direction of travel of the piece in the rolls of the mill. At the discharge end of the furnace, a ram enters from the side of the furnace and pushes the piece out of it to a snip shear and then directly to the first stand of the mill.

The roughing set of the mill consists of a vertical edging stand, two horizontal stands, a second edger, two more horizontal stands, a third edger, a single horizontal stand, and finally a fourth edging stand arranged in tandem in that order, making nine stands in all. Each edging stand is equipped with a separate variable-speed motor while the last horizontal roughing stand is also equipped with a separate motor. The other four horizontal stands, however, are arranged in two pairs, each pair being driven by a variable-speed motor through reducing gears. The horizontal stands are equipped with 12-in. diameter by 15 in. rolls. An electrically driven flying cropping shear is located at the end of the roughing set and a roll table is provided between it and the finishing set.

The finishing section of the mill consists of five two-high horizontal stands arranged in tandem, each separately driven by a variable-speed motor, the first two motors being connected to the stands through reduction gear sets and the final three stands being direct-connected. If the material is to be coiled, pinch rolls grasp the strip and feed it to automatic coiling machines which coil the strip tightly and discharge the coils to conveyers. On the other hand, if the strip is to be either run out to the hot bed in its entire length or sheared into appropriate lengths, before cooling, the pinch rolls and coiling equipment are replaced by a section of runout table. A flying shear is operated if desired and the material carried out to the hot bed.

The subsequent processing of the products from this type of mill follows a sequence of operations similar to those for obtaining

the products from the wide strip mill and will be described generally in the discussion on the finishing processes.

Continuous Hot Rolling of Wide Strip.—Since rolling in continuous tandem mills of considerable width is most typical of recent practice, the following discussion will pertain to the general operations of the mills which range from 50 to 100 in. This method typifies complete mechanization and rapid production to make 35,000 to 75,000 tons of products per month. It consists, essentially, in heating the slabs for rolling, hot rolling through a series of tandem stands of the four-high type, followed by subsequent processing according to class of hot mill product desired. The three classes of hot mill products made by these mills are plates, strips, and sheets. Each of these three classes is finished by a different sequence of processes. Each set of processes will be described.

Slabs for continuous hot rolling to strip are prepared by rolling ingots in the blooming mill to long slabs in widths which vary according to the product being rolled. For comparison, slabs for automobile sheets will be very wide while slabs for tin plate will be narrower. These long heavy slabs are conveyed to a shear for cropping and cutting into segments according to the specifications for length, thickness, and width, based on the dimensions of the finished product. In some plants these slabs are conveyed immediately to the mill; in others they are cooled, marked for identification of grade and dimensions, stored, then reheated to a temperature of 2150 to 2300°F. Reheating is usually done in continuous heating furnaces where a cold slab is charged into the back end by a pusher which forces a hot slab from the other end of the furnace. The properly heated slab is then conveyed by rolls to the head of the continuous mill line.

The heating furnaces, which may be either oil- or gas-fired, are designed to bring the slab to a good rolling temperature and at the same time produce a scale that can be readily removed by the scale breakers and hydraulic sprays in the mills. Each of the furnaces, of which there are usually three in the larger mills, is individually controlled so that the heater may increase or decrease the heat depending on the size of the slabs and the rate of their movement through the furnace. Charging of slabs in relation to heating is quite essential so that the rolling rate is consistent with the required finishing temperature.

Reduction of the slab by continuous hot rolling is in general accomplished by a series of roughing mills, as four stands of four-

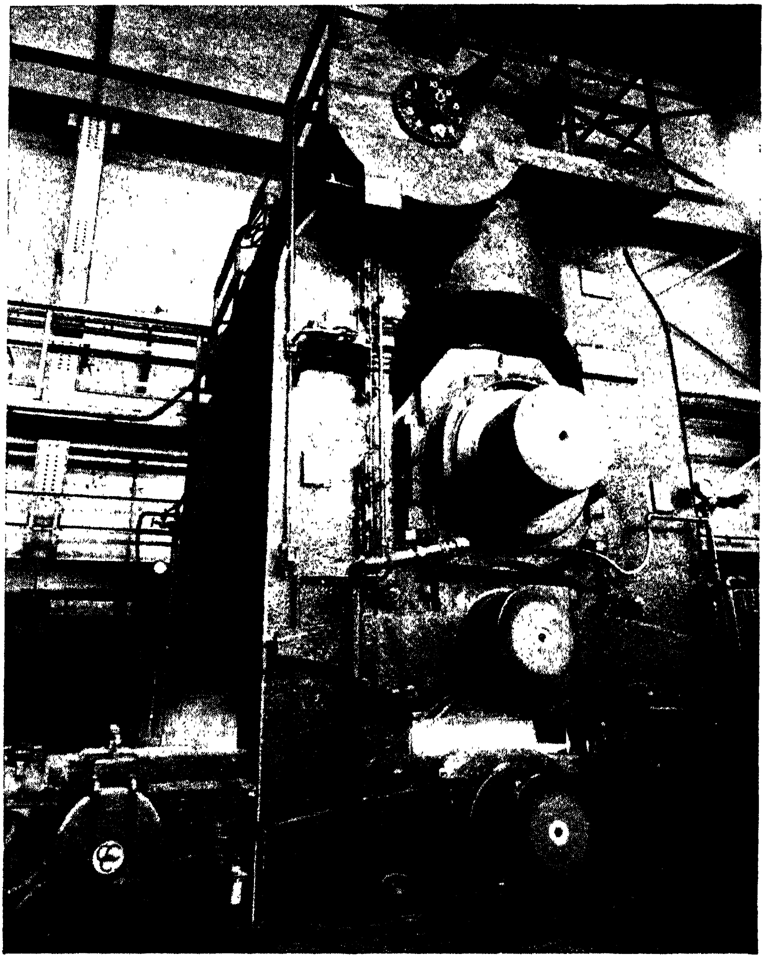


FIG. 6-XII.—The first four-high stand of rolls in the roughing train known as the "broadside" mill. (*Courtesy of Bethlehem Steel Corporation.*)

high rolls, followed by a series of finishing mills, as six stands of four-high rolls. The roughing stands are placed sufficiently far apart so that the slab is completely through one stand before it reaches the next one, while the finishing stands work the same strip at the same time.

Before a detailed study of the operations of the hot mill is made, it is essential that we understand the details of the "four-high" stand of rolls as this type of mill will be referred to in both hot and cold mill operations.

The mill consists essentially of four rolls mounted vertically in the housing (Fig. 6-XII). The two middle rolls, which are motor-driven, are the work rolls, and it is between these that the steel passes as it is being reduced. Above and below the work rolls and in contact with them are the back-up rolls which are not driven. The bottom back-up roll is below floor level in the figure. All the rolls are mounted in roller bearings. The screw-down mechanism is located on the top of the mill and is motor-driven. The pressure of the screw on the back-up roll bearing is transmitted through the back-up rolls to the work roll and in turn to the steel. Pressure blocks between the screw and the back-up roll bearing permit the pressures to be recorded on the control panel.

Before the rolling operation takes place, however, the slab must be freed of the primary scale that has accumulated during the heating process. This is accomplished by passing the slab through a scale-breaking stand of the two-high type equipped with a hydraulic spray system (Fig. 7-XII). This stand, which is primarily a set of pinch rolls, effects just enough draft to loosen the scale, which is then removed by jets of water, under pressures varying from 900 to 1,200 lb., playing on all sides of the slab on the delivery side of the stand.

The cleaned slab is carried on the roller table to the first stand of the four-high roughing mills which is commonly called the "spreading or broadside mill." In this stand the slab is given a drastic reduction in thickness, and the proper width of the finished product being rolled is established. The position of the slab on entering this mill depends upon the width of the finished product. If the finished product is to be less than an established maximum width, the slab enters the mill in the same position that it passed through the scale breaker. If the width is to be greater than that established above, the slab is turned 90 deg. horizontally by a turntable and passes through the mill "sideways." Before the cross-rolled slab moves to the next mill, it is turned back to the original position by another turntable located on the delivery side of the spreading mill. If the steel

is too hot for best rolling in the finishing train, the slab is held until it has cooled to the proper temperature.

A few feet from the second turntable is located a hydraulically driven slab squeezer which is almost indispensable when spreading or cross rolling. The entire slab in this machine is leveled and

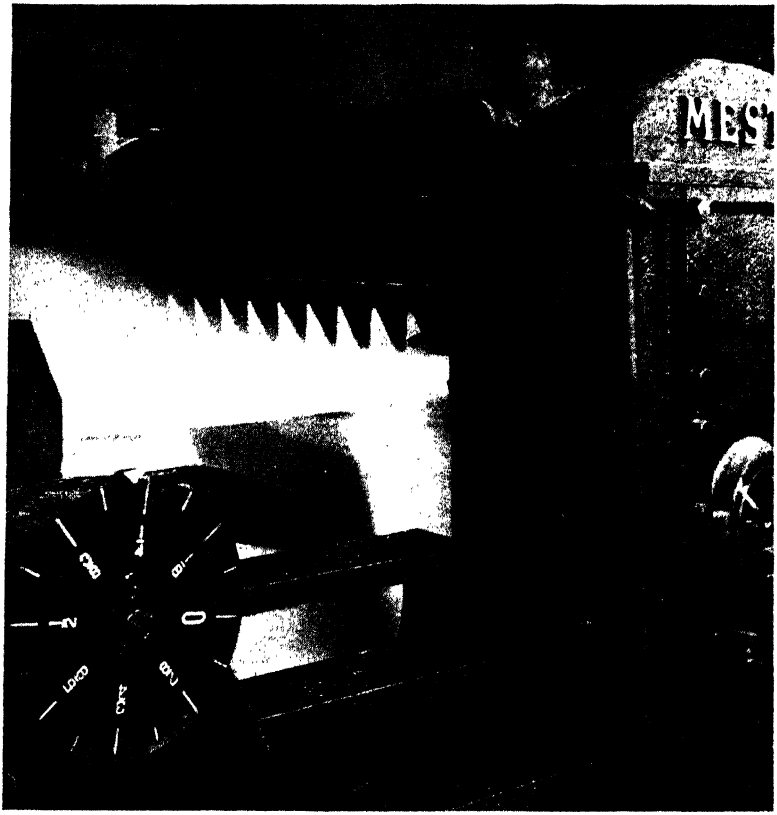


FIG. 7-XII.—Scale breaker. (*Courtesy of Bethlehem Steel Corporation.*)

the sides trued by the application of pressure. This is a necessary operation because the slabs have uneven edges and surfaces after being rolled in the spreading mill, which if not trued and leveled would affect the quality and specifications of the finished hot mill product.

From the squeezer the slab is moved rapidly through the remaining three roughing stands. These mills are similar to the

spreading mill, except that they have vertical edging rolls on the entry sides which maintain the width of the slab as established in the squeezer (Fig. 8-XII). Therefore, as the slab is reduced in the succeeding roughing and finishing stands, it is extended in

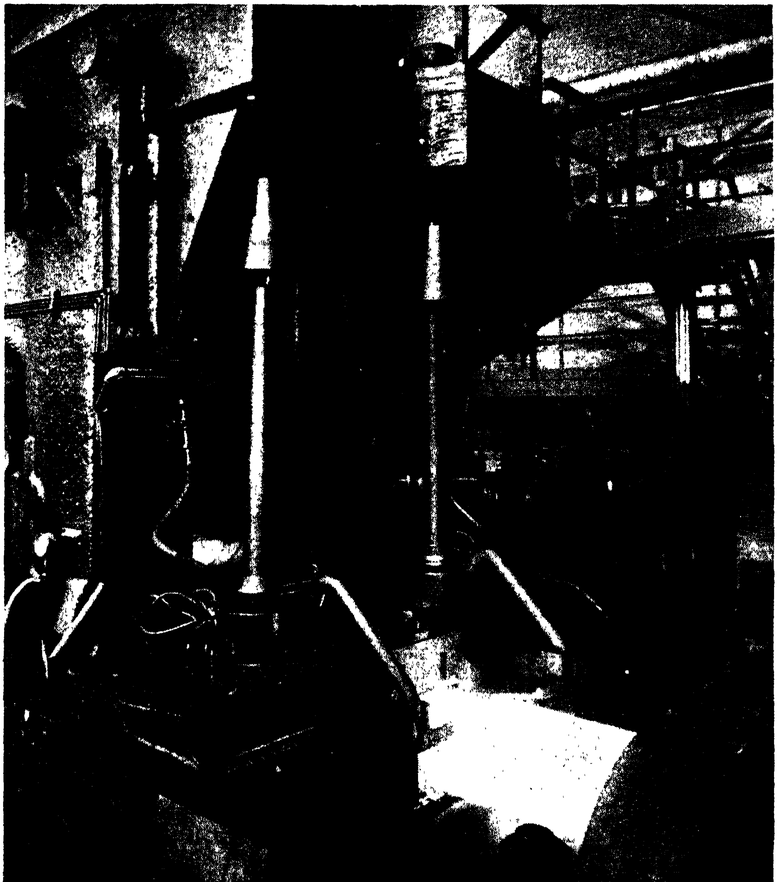


FIG. 8-XII.—Slab entering a roughing mill. Note the two perpendicular shafts for rolling sides of slab. (*Courtesy of Bethlehem Steel Corporation.*)

length, with the width remaining constant. As the slab becomes longer, the distance between the roughing stands increases so that the steel is engaged in one roughing stand at a time. At the delivery side of each of the four roughing stands, water under high pressures is played on the surface of the slab to remove

any scale that has formed since the first descaling in the scale breaker.

The procedure of hot rolling in the roughing stands varies in different plants. These variations are largely concerned with the use of some two-high stands in place of the four-high stands, and in the number and distribution of the roughing stands.

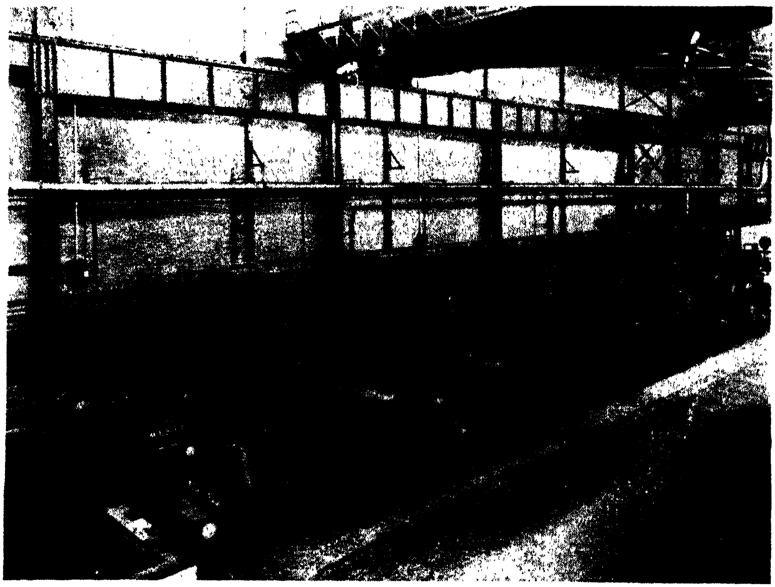


FIG. 9-XII.—The finishing train of six rolling mills and scale breaker. (*Courtesy of Bethlehem Steel Corporation.*)

After the steel leaves the delivery side of the last roughing stand, ready for rolling on the finishing stands, it moves out on a long roller table where the temperature is checked by a recording and indicating pyrometer. After reaching the proper temperature, the slab enters the hot finishing train where it is reduced to strip. This train of stands is much more standardized than the roughing stands, six four-high stands having been found to be most satisfactory (Fig. 9-XII). These six stands are placed quite near together and are so closely synchronized that they may be considered as a single unit, even though each stand is individually driven.

Before entering the first finishing stand, the slab is given another cleaning and descaling in a second scale breaker. The

scale-free slab then passes rapidly through the finishing train. Owing to the rapid elongation as it advances, the steel is quickly engaged between the rolls of all the stands of the train at one time. Each of the succeeding stands is operated at a greater speed than its predecessor to compensate for this elongation. Motor-driven looper tables, placed between the stands, maintain the desired tension on the strip (Fig. 10-XII). This is accom-

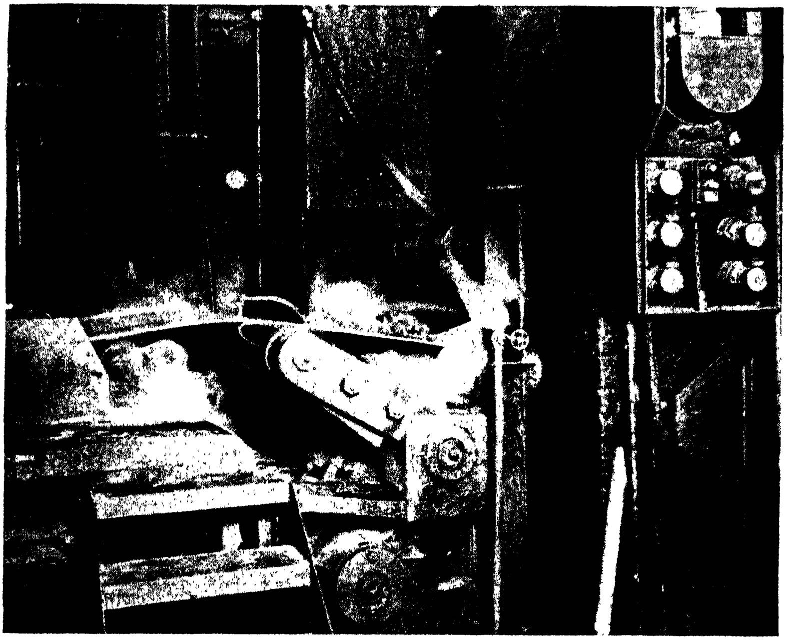


FIG. 10-XII.—A looping roll to take up slack and maintain tension of the moving strip in the finishing train. (*Courtesy of Bethlehem Steel Corporation.*)

plished by raising or lowering the friction rolls on the loopers. Control of the tension and regulation of the rolls with respect to draft and speed are made by operators from a central switchboard located so that these men have a clear view of the entire operation.

As the strip emerges from the last stand of the finishing train, it is of the specified gauge and width and is ready for the finishing operations required to meet the order specifications. Excellent control is maintained over the gauge of the metal by the use of automatic gauges which indicate to the operator what changes are

necessary. These changes are rapidly made through motor-driven roll adjustments. The strip seldom varies more than 0.001 or 0.002 in. from center to edge. The speed of the last finishing stand varies according to the gauge being rolled and may reach over 2,000 ft. a minute in some mills. The temperature of the strip while going through the finishing stands also varies with the section being rolled. For example, in rolling 16-gauge material, the temperature out of the last roughing stand may be 2050°F.; out of the last finishing stand it may be 1450°F.

Since surface quality of the strip is of paramount importance, careful attention is paid to the work-roll surfaces, particularly in the finishing train, and frequent roll changes are necessary. The work rolls in the roughing stands have relatively slight effect on the finished surface and hence are changed less often. The back-up rolls or pressure rolls are changed much less frequently since they do not touch the hot steel. When the rolls are removed from the stands, they are reground and surface-polished, after which they are returned to roll stands located near the reducing stands in which they will be used.

A better picture of this type of mill may be had by considering the following data on the Jones and Laughlin 96-in. hot strip mill:

Mill	No. rolls	Work roll dia., in.	Back-up roll dia., in.	Roll length, in.	Strip speed, ft. per min.	Distance from preceding stand
Scale breaker	2-high	24		96	267.9	31′4″
Rougher	4-high	38	51	96	190.5	44′5″
Rougher	4-high	28	51	96	351.8	52′6″
Rougher	4-high	27	53	96	453	82′6″
Rougher	4-high	27	53	96	453	110′11″
Scale breaker	2-high	25½		94	114–455	14′8″
Finisher	4-high	27	53	96	234–468	18′0″
Finisher	4-high	27	53	96	391–782	18′0″
Finisher	4-high	27	53	96	570–1,140	18′0″
Finisher	4-high	27	53	96	741–1,482	18′0″
Finisher	4-high	27	53	96	884–1,768	18′0″
Finisher	4-high	27	53	96	1,037–2,074	18′0″

Rolling of steel in the hot mill, from the first scale breaker to the last finishing stand, is generally the same whether the slab is to become plate, sheet, or strip.

If the product is to become plate, the long strip of steel is run out on the main hot mill runout table, transferred to secondary tables where it is sheared to plates of varying length, roller leveled, and cooled. The finishing operations—which depend on specifications—may include cutting to smaller dimensions, side trimming, roller or stretcher leveling, and resquaring.

When sheets are being rolled, the strip is cut by a flying shear located at the end of the finishing train, which is synchronized with the rolls of the last finishing stand so that the steel as it emerges may be cut to the lengths desired. The sheets are carried on the runout table to pilers where they are stacked, picked up by a crane, and carried to cooling bays where they are allowed to cool before finishing. The finishing operations again depend upon specifications and will be described later.

If the material is to be cooled for further continuous processing, the hot steel is carried on the main runout table to coilers where it is rapidly wound while still hot. Coiling of strip, although it makes convenient handling in future processing, is done principally to bring about a self-annealing so as to induce a softening and a uniformity of grain structure. Most of the coiled, hot-rolled strip becomes material for reduction in continuous cold mills. The subsequent finishing operations may include the following processing which may or may not be continuous: pickling, cold rolling, normalizing, annealing, temper rolling, side trimming, and roller or stretcher leveling. Further processing will depend on the use of the material. If the specification calls for sheets, the material is cut to the required lengths by a rotary shear after the foregoing finishing operations.

Pickling.—Since the function and general features of pickling have been discussed previously, we shall confine this discussion to the general sequence of operations as they pertain to sheet and strip.

The removal of the iron oxide scale that accumulates on the hot-rolled steel sheet by an acid is called "black pickling." This operation prepared the hot-rolled strip for cold rolling and pack-rolled sheets for annealing. If the sheet or plate is to be galvanized, tinned, or terneplated following treatment, such as annealing or cold rolling, it is given a second pickling known as "white pickling."

The pickling of sheets is usually done in batches, although continuous pickling of long sheets from the continuous mill can

be carried out as in the subsequent discussion on the pickling of strip. The sheets are black-pickled by stacking them sideways on racks and immersing them in tanks of hot dilute sulfuric acid. The solution generally runs from 4 to 8 per cent sulfuric at a temperature of between 120 and 180°F., with the time varying from 10 to 30 min. according to the amount and type of scale. In order to effect a thorough cleansing action, the sheets are stacked loosely so that the acid will be in contact with all points.

FIG. 11-XII.—Modern plunger-type pickler. (*Courtesy of The Mesta Machine Co.*)

The pickling machine usually used for sheets is either of the plunger type, which is the most widely used, in which the sheets are plunged up and down in the solution, or the surging type in which the solution is caused to move up and down around the sheets. The plunger type, as is shown in Fig. 11-XII, moves the rack of sheets up and down by means of a centrally located hydraulic or steam plunger. The horizontal arms extending from the machine make it possible to carry on a sequence of operations by turning the machine 90 deg. at given intervals. Thus, the cycle may be to treat the initial scale in the first tank, give a second treatment in a fresher and more dilute solution at the

same or lower temperature, a washing treatment in water as a third, and possibly an alkaline rinse in the fourth.

Black pickling of hot-rolled strip is carried out in continuous pickling vats. As the strip is uncoiled at the beginning of the continuous pickling line, ends are sheared square and adjacent ends of successive coils are either lapped and stitched together, or butted and arc-welded. The strip is automatically and continuously conveyed by rolls through a series of three or four acid tanks, a scrubbing tank, and a washing tank. The acid concentrations and temperatures are approximately the same as those used in the plunger-type machine, but the time in the acid is very much shorter, being only 3 or 4 min. Modern tanks are of steel construction and made of acidproof brick set in sulfur-base cement, or they may be steel tanks rubber lined or acidproof brick lined. The entire series of vats are fitted with covers. As the strip emerges from the picklers, it is dried by hot air, oiled, and recoiled.

White pickling of sheet or plate is done with the plunger-type machine since strip for galvanized sheets, tin plate, or terneplate is cut into specified lengths before the coating operation. Since there is relatively little oxide to remove, a weaker acid, a shorter time, and a lower temperature may be used. It is essential that there be no overpickling in this operation as a deeply etched surface would require more coating material than normal. Inhibitors are, therefore, commonly used in this operation.

Cold Rolling.—Cold rolling of steel is practiced to secure certain properties in the finished product that cannot be obtained by hot rolling alone. These properties might be classed as follows:

1. *Dimension*, or gauge. The over-all dimensions of cold-rolled material are considerably more uniform. This is particularly true of the gauge thickness.

2. *Hardness*, or temper. As the amount of cold work increases, the hardness of the material also increases. This allows the production of the same material in several degrees of hardness and springiness by controlling the degree of cold work. Rolling for temper, then, requires a reduction, after annealing, of from 3 to 50 per cent, depending upon the degree of temper required and the grade of steel being cold-rolled. In any one class of temper the actual reduction given to produce the desired temper depends

upon the initial thickness, the final desired thickness, and upon the steel itself.

3. *Finish*, or surface. The essential characteristic of cold rolling so far as finish is concerned, is the production of a smooth, bright surface. The final condition of the surface after cold rolling is dependent upon the surface condition of the hot-rolled material, on the efficiency of the cleaning process, and upon the degree of polish of the cold rolls. Three grades of finish are considered to be representative of the results produced by cold rolling: (*a*) extra bright, a very smooth and bright finish suitable for electroplating and one that does not require polishing. This grade is also known as silk, satin, or mirror finish. (*b*) Standard bright, a very smooth finish suitable for electroplating and for lacquer finish; (*c*) regular, a smooth and bright finish for ordinary uses, either plain or for enameling.

4. *Edge*. Natural edge, the mill or natural edge; sheared edge, produced by slitting wider strip into narrower strips or just by a rotary slitter for sheared edge; sheared and filed edge, the same as a sheared edge except that it is filed to remove any burrs and to produce an almost round edge; rolled edge, produced by edge-rolling the strip during cold rolling, furnished in either round or square edge.

Cold-rolling Mills.—The type of cold mill used for a particular product depends to a large extent upon the desired characteristics of the product and the equipment available at the time of installation. The three most widely used types of cold-reducing mills to be briefly discussed are (1) tandem mill, (2) single stand reversing, (3) Steckel mill.

Continuous or Tandem Mill.—This type of mill for the cold reduction of coiled, hot-rolled strip into lighter gauges usually consists of a train of from three to five heavy four-high stands of rolls (Fig. 12-XII). These mills are not reversing, the coil of strip being threaded through the stands, with the reductions in each stand being such that the finished gauge is obtained in the last stand. The rolls in these stands may be very finely adjusted and will regularly produce material with gauge variations of no more than 0.0005 in.

The cold-rolling stands, like the finishing stands in the continuous hot mills, are placed quite close together in tandem, and

operate practically as one unit. This permits cumulative reduction of the steel with one pass. Steel is fed through stands of the mill and is automatically recoiled at the delivery end. There is perfect synchronism between the individual stands with the speeds increasing in succeeding stands to compensate for the increasing length of the material as it is rolled and to keep the material from pulling apart between stands. Most of the reduc-

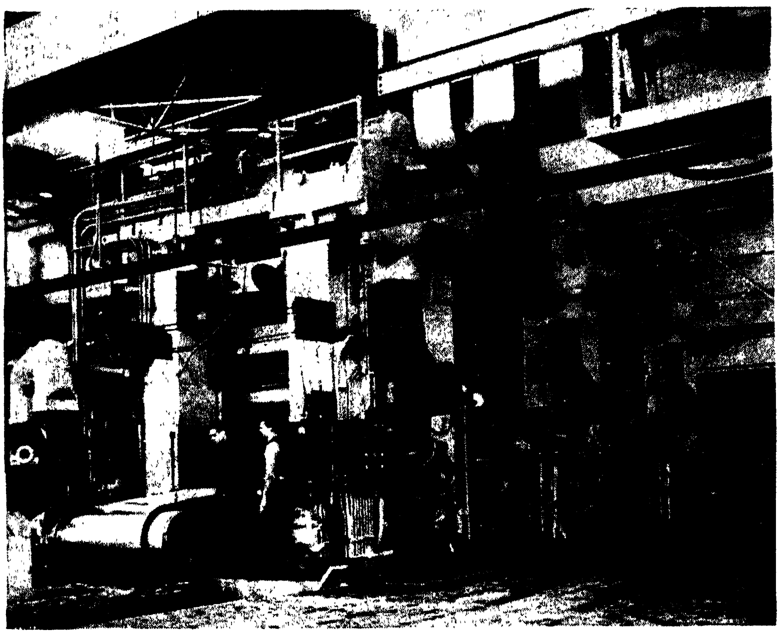


FIG. 12-XII.—A tandem train of three stands of four-high mills for cold-rolling strip. (*Courtesy of Bethlehem Steel Corporation.*)

tion is made in the first stands of the mill with the last stand being used largely for fine finish and accurate gauge control. Automatic electric sheet gauge devices are used to provide an accurate and continuous check of the gauges of the reduced strip. The speed of cold rolling is much slower than that of hot rolling and varies according to the gauge being rolled.

A general picture of this type of mill may be had by considering the following characteristics of Jones and Laughlin 54-in. tandem cold mill:

Characteristics	Work roll dia., in.	Back-up roll dia., in.	Roll length, in.	Strip speed, ft. per min.	Distance from preceding stand, ft.
4 stands—4-high	$20\frac{1}{2}$	53	54		
Stand 1	....	..	..	183–366	
Stand 2	...	..	..	296–592	16
Stand 3	....	..	..	388–776	16
Stand 4	....	..	..	463–926	16

The advantages of the tandem cold-reducing mills are their large capacity and very low labor cost, although the original cost is quite high. The disadvantages are the lack of flexibility for rapid changes in section and the fact that the stock must receive a fixed and limited number of passes.

Single-stand Reversing Mill.—This type of mill is similar to a single stand of a tandem line, being of the four-high reversing type with driven work rolls as well as either front or back tension or a combination of front and back tension. The same type of work is accomplished on the mill as in the tandem train, but more slowly. In the tandem train the strip is reduced in a single pass to the finished product while in this mill the work is reduced in steps. The hot-rolled and pickled coil is fed into the mill and clamped into a coiling reel as it comes through the rolls on the opposite side of the mill. As the end of the strip approaches the rolls, the mill is stopped and reversed. This end of the strip is clamped into the back coiling reel. Subsequent reversals are then made until the desired gauge is obtained. The number of passes will depend upon the gauge. The same precise, automatic control devices are used on these mills as are used when cold rolling in tandem mills. Rotary micrometers are located on each side of the mill and indicate on the control board variations in the gauge as the strip comes from the rolls. The strip is cooled and lubricated, and the roll contour maintained by hot- and cold-oil jets mounted at various points on the mill. When reduced to finished gauge, the strip is cut at the exit end of the mill and removed for further finishing operations.

The advantages of such a mill are that less floor space is required than for a tandem mill; it has greater flexibility as to the number of passes, a slight possibility of better gauge control,

and a lower initial cost. The disadvantage is the high labor cost due to the limited capacity of the mill.

Steckel Mill.—This type of mill, named after its inventor, A. P. Steckel, is of the four-high reversing type. A diagrammatic sketch of the method of operation of the Steckel mill is shown in Fig. 13-XII. The rolls are not driven, the strip being drawn through them by applying power to the reels. This is made possible by the small roll pressures necessary, even for heavy reductions. Heavy housings are provided for the rolls, the

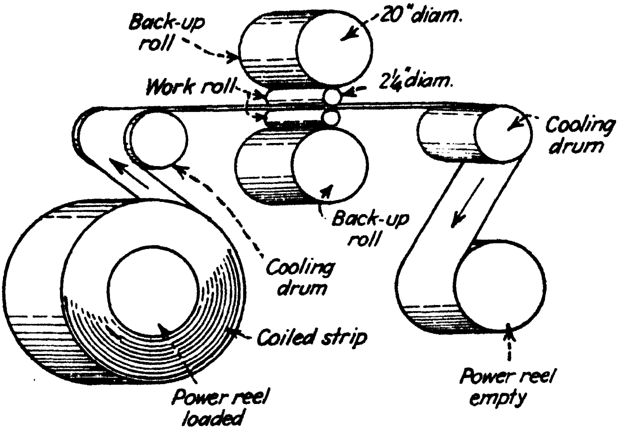


FIG. 13-XII.—Diagrammatic sketch of the Steckel mill. (*From Iron Age.*)

diameters of which are indicated in the figure for a mill with rolls 7½ in. long in the body. Both pairs of rolls are made slightly larger when the length of the rolls is increased to accommodate wider strip or sheet. The work rolls are made of highly polished high-speed tool steel and are held in place by babbitt-lined bearings, since the only stress on these rolls is the side pull of the strip. The heavy backing-up rolls are of special heat-treated steel and are held in place by very heavy roller bearings. Either a motor-driven or hand-operated screw-down is provided.

The power reels are driven by a variable-speed electric motor through a set of gears arranged in such a way that the strip can be wound on either reel at will. Both reels are mounted on roller bearings and are provided with brakes to effect a back tension on the strip. The reels and cooling drums are arranged as shown in the sketch. The cooling drums are internally cooled by

flowing water in order to cool the strip; they rotate as idlers with the movement of the strip and also serve as guides to direct the strip between the rolls in a horizontal direction without bending as it enters or leaves the working rolls.

In operating the mill, a coil of strip is mounted on one reel, fed through the mill, and clamped to the other reel. The empty reel is started, using a sufficient tension to draw the material through at the desired speed and draft used and also to overcome the back tension produced by the other reel. When the strip is reeled, the screw-down is operated the desired amount and the direction of operation reversed. In this way, the strip is fed back and forth through the rolls until the desired gauge is reached, the screw-down being operated after each pass.

The Steckel mill is similar to the single-stand reversing mill in that it has flexibility as to the number of passes and occupies a small floor space. This type of mill may be built at a slightly lower cost than the single-stand reversing mills. The speeds at which it operates are somewhat greater, but usually less drastic reductions are accomplished by each pass than with the four-high reversing mills. The Steckel mill is classified as a means of rolling only the lightest gauges of mild steel but it is also useful in rolling stainless steels, high-carbon steels, and razor-blade stock, regardless of the finishing gauge. This mill may be classified as a production unit if, in its use, two or more intermediate anneals may be eliminated. The capacity of this mill is approximately one-third that of the tandem mill and one-half that of the single-stand reversing mill.

Annealing and Normalizing.—Steel that has been cold-rolled in strip or pack-rolled in sheets is hard and fairly brittle because of the internal strains that have been produced by the working. In order to provide the right physical properties for forming and drawing into finished products, these materials are heat-treated.

In general the heat-treatment of the sheets or strip should be adjusted to give the grain size and structure that will produce the desired physical properties in the finished material. The following factors should be considered in specifying the treatment to be used:

1. The chemical analysis of the steel.
2. The methods of rolling.
3. The gauge of the material.

4. Subsequent processing.

   a. Nature and degree of bending, forming, or drawing.
   b. Surface condition desired on finished article.

5. The cost of the material in relation to cost of the finished product.

A sheet that may be properly treated for one class of work may not be at all suitable for another purpose. Similarly, sheets treated in a given way may work very satisfactorily under the dies and methods used in one shop but may not give satisfactory results for the same kind of work in another shop, owing to variations in dies and methods employed. The only way to determine the proper treatment for a given purpose is to make a trial fabrication run with a representative lot of the material.

There are two general methods of heat-treatment used. The first method, known as box annealing, is the more common. In this process the products—if sheets, are stacked in piles; if coiled strip, are stacked edgeways—are covered with suitable containers and heated slowly to temperatures ranging from 1000 to 1400°F. for a predetermined length of time and slowly cooled. The total annealing cycle may be several days in length. The second method of heat-treatment is normalizing, in which the sheet is quickly heated to temperatures ranging from 1600 to 1750°F. and cooled rapidly.

Annealing.—This process, which is a very slow one and not readily adapted to continuous methods, involves first the stacking of the material on heavy cast-iron or steel bases with turned-up edges and covering with cast-iron bases. If the material is in sheet form, it is piled 4 or 5 ft. high (Fig. 14-XII). If the material is coils of cold-rolled strip, it must first be run through a continuous cleaner which removes the coating of oil electrolytically and then scrubs, dries, and recoils for annealing. The coils are then stacked on end, sometimes two-high, or often the strip is cut into sheets before annealing, since sheets take less space in the boxes and are more conveniently cut and handled before annealing. However, coils are less likely to stick and are more conveniently given a final surface treatment after annealing than are individual sheets. After stacking, the covers are placed over the charge and sealed with sand at the joint where the cover meets the base plate. This sealing is done in an effort to prevent

as nearly as possible the oxidation of the steel surfaces. The box is then run into an oven-type annealing furnace where it is brought up to the predetermined annealing temperature, given a soaking period at temperature, withdrawn, and cooled very slowly to room temperature. A total time of as much as 96 hr. may elapse from the time the box is charged until the material is cool enough to handle for subsequent processing. During this

FIG. 14-XII.—Box annealing of sheets. (*Courtesy of The Youngstown Sheet & Tube Co.*)

period the steel grains recrystallize to form a uniform fine-grained structure, free from distortion or strain, hence making the sheet or coiled material soft and ductile.

There are some continuous-type annealing furnaces in operation. Annealing is done in a furnace several hundred feet long in which the box slowly moves through heating, soaking, and cooling zones.

In the past few years the old oven-type furnaces and heavy cast-iron covers have been replaced by portable covers, electrically or gas-tube heated. Several stands or bases are used for each cover. The stacked sheets or coiled strip are placed on

the base and covered with a light sheet-iron or alloy steel cover. Finally the portable heating cover, containing the necessary heating elements, is set in place over the charge (Fig. 15-XII). After the charge has been heated and soaked for the predetermined length of time, the heating cover is removed and placed immediately over another charge of material. The inner protecting cover is left over the material. One portable cover may, thus, handle several stands of material. By using such furnaces, the heating control is much better, the charge is more uniformly

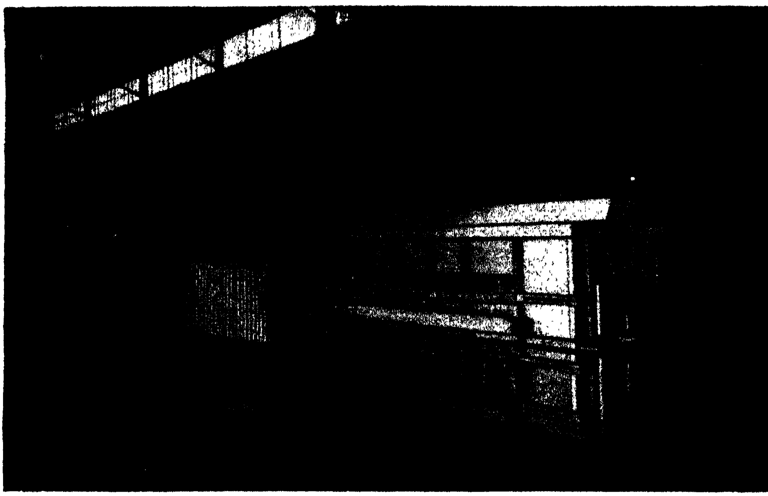


FIG. 15-XII.—A modern annealing furnace, the inner curve on a second base, and the charge uncovered on the third base. (*Courtesy of Lee Wilson Engineering Co.*)

heated, the cooling accomplished more quickly, and the fuel efficiency is greater than in the older method.

Another important recent development is protection of the charge being annealed with a deoxidizing gas. The use of a protecting gas, such as natural gas, has been used to a limited extent for some years, particularly during the cooling period, but with recent developments of cheap gases bright annealing has become commercially satisfactory. The process consists in, first, the cracking of certain gases, such as natural gas or by-product gas, and the subsequent removal of the sulfur, water vapor, and carbon. This dehydrated and partly combusted gas is then

passed into the chamber around the charge during the annealing cycle. The surface oxidation is thereby held to an absolute minimum.

The usual annealing treatment for pack-rolled sheet and coiled strip is termed a "black anneal" since it has for its purpose the softening of the black uncoated material. Frequently, when the material is given a subsequent cold reduction for surface finish, it is necessary to follow with a second annealing treatment. This second treatment is differentiated from the first by terming it the

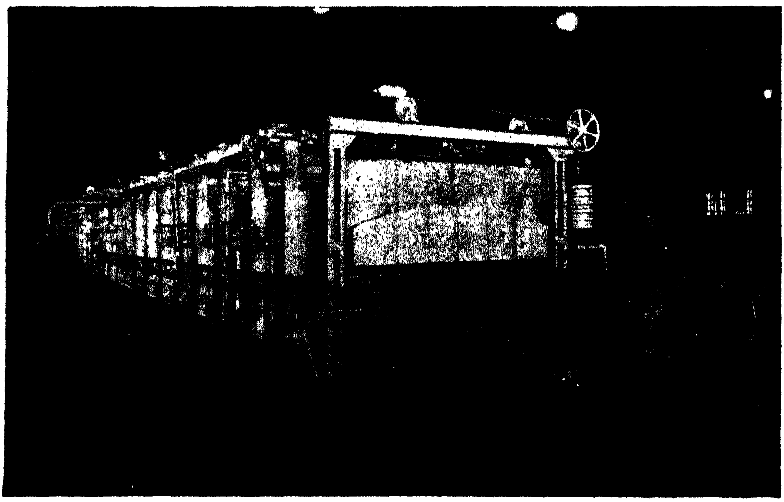


FIG. 16-XII.—The discharge end of a continuous-sheet normalizing furnace. (*Courtesy of The Surface Combustion Corp.*)

"white anneal." This second treatment is carried out similar to the black anneal except that the temperatures are much lower, probably reaching a maximum of 1000°F. The cycle in this treatment is likewise considerably reduced, ranging around 60 hr.

Normalizing.—This process is carried out in long furnaces through which the strip or sheet passes continuously. These furnaces are either of the horizontal or vertical type and are heated by gas or electricity. As the horizontal type is the more used, we shall confine our discussion to it.

The continuous furnace (Fig. 16-XII) consists of a heating chamber and a cooling chamber of varying lengths, depending upon the heating and cooling cycle desired. These two zones are usually separated by a restricted passage which minimizes the

penetration of heat into the cooling zone. Some type of continuous conveyer mechanism is used to convey the material through the furnace. Various types of atmosphere control may be used such as the use of dehydrated gas, hydrogen gas, use of a smoky gas flame in the heating zone, and the use of a slight internal gas pressure along with mechanical barriers such as asbestos sheet or water seal at the entrance and exit ends.

After the charge has passed through the cooling tunnel and into the air, the material if sheets is stacked, or if strip it is coiled, for subsequent processing. Only a short time is required for the entire cycle. Hence normalizing is well adapted to rapid, continuous operation.

Normalizing serves to improve the drawing qualities of the hot-rolled properties for many applications by producing through the rapid cooling a fine-grained surface and more stiffness than the soft interior.

Cold Rolling (Finish).—The finish cold rolling of the annealed or normalized material has several purposes. (1) Cold rolling in general has as its principal function the production of an improved surface. (2) It has the function of removing dents, creases, and some types of "waves" which have resulted from hot rolling and opening of the pack in the case of pack-rolled sheets and from the separating of the sheets after box annealing. (3) The effect of cold rolling, in imparting stiffness and strength to the material, is used to produce the tempers required for certain purposes.

This "temper pass," or "skin pass" as it is sometimes termed, produces the desired results by varying the intensity and number of cold-roll passes given the material. The reductions in this type of pass depend upon the ratio of stiffness to ductility specified and range from 0.5 to 3.0 per cent. When the material is cold-rolled merely to smooth and polish the surface and extreme ductility is desired in the finished product, it is followed by an anneal (white) after cold rolling to remove the stiffness. By carefully planning the combinations and variations of annealing and cold rolling, a wide variety of physical properties and surface qualities may be produced to suit the requirements of drawing, forming, and coating operations.

In the final cold rolling of black annealed sheets, the packs of material are first opened or separated and passed individually

between the polished rolls of either a two-high or four-high mill. The type of mill used depends upon the specifications of the steel and the type of equipment available. The conventional type of mill used is a two-high stand of chilled, highly polished rolls somewhat similar to the type used in the hot mills (Fig. 17-XII). One or more passes are given the sheets according to the specifications desired. This procedure varies with plants. Some employ a series of single two-high stands of rolls set in tandem.

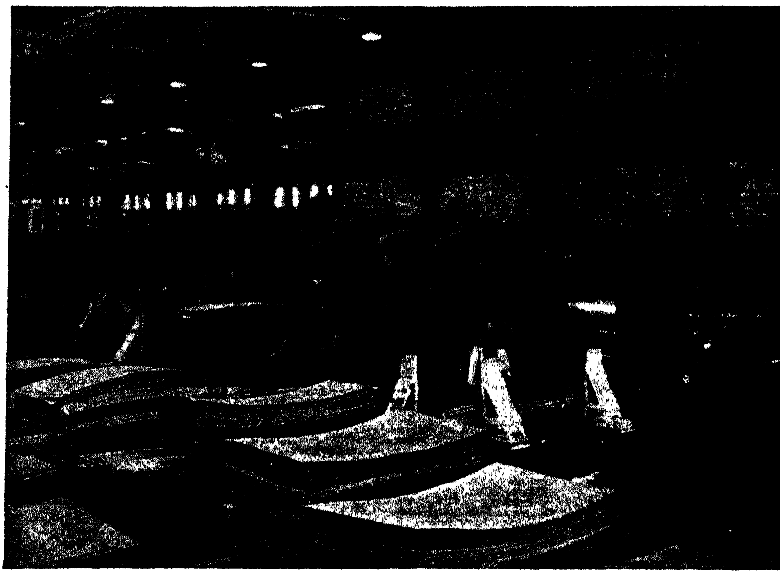


FIG. 17-XII.—An installation for cold-rolling sheets. (*Courtesy of The Mesta Machine Co.*)

In more recent installations the four-high mill is being used for both sheets and strip. These mills, which are in general single stands, are similar in type to the four-high stands previously discussed. Sheets are fed singly, while coiled material is run in a continuous strip.

Flattening or Leveling.—The procedure subsequent to cold rolling depends upon the specifications. If the material is ordered in coil form, it will be side-trimmed and roller-leveled directly following the temper pass. If the material is to be in sheet form and has been treated in coil form up to this point, it will be transferred to a trimming and shearing line which consists of an

uncoiler, pinch rolls, side trimmer, roller leveler, flying shear, pinch rolls, and piler. Sheets produced by pack rolling, as we have already learned, are sheared to the desired size after hot rolling. However, after the completion of all operations, which may include cold rolling, stretcher leveling, etc., it may be necessary to resquare by carefully shearing to meet the specifications.

Roller Leveling.—The roller-leveling machine commonly in use to remove the distortion produced by the finished operations in the sheets and strip has a number of top and bottom rolls. The upper and lower rolls are staggered so that in passing through the leveler, the sheets are flexed alternately up and down. The rolls at the entrance side of the leveler have their axes closer together than do those at the exit side. This results in heavy flexing in the early rolls with lighter flexing and straightening at the exit side. By proper control of the staggering of the rolls, flatness may be obtained with essentially no increase in length.

Stretcher Leveling.—Although the sheets leveled in the roller leveler are flat enough for ordinary purposes, specifications sometimes call for sheets of perfect flatness. This requires stretcher-leveling, a process by which the sheets are gripped on each end by jaws attached to pistons that are forced apart by hydraulic pressure. The effect is to stretch the sheet and gradually take up all the slack that may exist until it is stretched taut and its shape is practically a flat plane. The sheet in this way takes a permanent set in its flat condition which will not be materially changed after stretching is stopped. As the clamps deform the ends of the sheet, it is usually resheared to dimensions after leveling.

Inspection.—The following discussion of inspection of sheets will be necessarily brief as the subject is much too broad for detailed description in a work of this scope. The inspection requirements will, of course, vary according to the customer's specifications. In the more common grades of uncoated sheets no inspection is made, except for the cursory inspection made by the workmen as the sheets pass through the different stages of manufacture and as they are being prepared for shipping. The conspicuously bad sheets are assorted and discarded. In the case of highly finished sheets, for use in the automobile, furniture, etc., trade, higher standards have been specified and it is necessary to make a sheet-for-sheet inspection. In this inspection the

requirements usually are that the sheets be first quality on one side. They are stamped as such if they meet the requirements. The sheets are classified as primes, or first quality sheets, with at least one side up to standard; seconds, or sheets with some minor defect with respect to surface or flatness or other feature not within prime classification; wasters, which have more serious defects but which may have some commercial value; and scrap. If the material is specified in coil form the usual grading into primes and seconds is impossible; hence very close inspection is made while the material is being processed.

The defects that occur in sheets are too numerous to describe properly in this brief discussion. An additional difficulty in making such a discussion arises in the fact that there is considerable variation in the standards of inspection set up for the different grades. In brief, however, the general types of difficulties encountered both by the customers and at the mill are as follows:

Customer complaints generally involve:

1. "Breakage during forming," which usually is the result of three conditions: (*a*) age hardening, which denotes the susceptibility of certain grades to suffer a change in hardness and ductility over a period of time and results in increased hardness and decreased ductility after processing. The drawing qualities are thus decreased and the breakage resulting will depend upon the extent of the hardening. (*b*) Dirty steel, which results in breakage on forming and may be due to faulty steel practices as well as insufficient blooming mill cropping. (*c*) Failure to develop maximum ductility, which results in breakage on drawing and may be attributed to the fact that the processing setup did not develop maximum ductility.

2. "Surface imperfections after forming," which involves the appearance of certain defects on forming material from sheets which as far as visual inspection is concerned were considered primes. These defects are revealed as (*a*) slivers of various types; (*b*) "surface laminations" or "surface pipe" usually appearing as a raised welt of elongated dimensions; (*c*) "mottled or roughened surface" usually appearing on the surface of the drawn part as a blemish of rough uneven appearance and usually at the point of greatest draw. This defect may be either the result of faulty steel practice or improper processing. If it is

due to improper processing, the roughened appearance will be banded in character and is termed "stretcher strains."

Mill complaints involve:

1. Difficulty in meeting the physical property specifications, such as Rockwell, Olsen, and tensile values. In general this is the result of structural weakness which will result in these inferior physical properties. This is brought about by (*a*) incorrect finishing temperatures on sheet or coil material, (*b*) excessive reductions in cold mill practice, (*c*) improper annealing practice for the grade being processed, (*d*) excessive cold work in the temper pass, (*e*) dirty steel, (*f*) occasional instances of steel that is hard and has low ductility after the anneal. The presence of alloys is the usual contributing factor in this latter case.

2. The numerous surface defects that arise in spite of careful processing. The more frequent surface defects resulting from the processing are as follows: (*a*) hot mill defects, appearing as cracked or burned edges, seams, slivers, laminations, scabs, loose oxide, roll marks, gouges, etc.; (*b*) cold mill defects, appearing as surface or skin pipe, roll marks, and other defects resulting from the original slab, the hot mill, or inferior pickling; (*c*) normalizing or annealing defects, in general the results of improper heating which results in undesirable scale; (*d*) pickling defects, appearing as improper dulling or etching and surface discolorations.

Production of Stainless Steel Strip and Sheets. *Strip.*—For practically the same reasons as were outlined in discussing the production of stainless plate, the rolling of stainless strip presents some difficulties not encountered in rolling plain carbon strip. This material is usually finished in widths of 15 in. and under and of varying thickness, although wider material is sometimes desired. The high-speed continuous strip mills are not well adapted to the hot rolling of stainless because of the necessity of slow rolling. A universal reversing roughing stand and three or four smaller finishing stands make up the usual hot-rolling equipment. The material in the hot-rolled form averages from 0.10 to about 0.18 in. in thickness.

Since the strip is finished at about 1500°F. and since this finishing temperature produces some hardening effect in stainless steels, the strip must be heat-treated before cold rolling to

reduce its hardness. In one installation,[1] the coiled strip from the hot-rolling mill is placed in a coil box and fed through a roller leveler which takes the kinks out of the strip since it is quite springy as coiled. From the leveler, the strip passes directly to a continuous gas-fired furnace through which it passes at about 6 ft. per min., being heated to temperature ranging from about 1700 to 2000°F., depending upon the material. The furnace is capable of handling two strips at once (side by side). At the discharge end of the furnace reels are situated to coil the material, but at sufficient distance to allow for air cooling of the strip before coiling. The reels furnish the power by which the strips are pulled through the furnace. When one strip is nearly fed through, the end of a new strip is riveted or tack-welded to it in order to make the operation continuous. A shear is placed before the coiling reels to shear the ends of the strips on each side of the rivets or weld.

In some cases, a continuous pickling machine is placed right after the furnace and the material is heat-treated and pickled in one continuous operation. The sequence of operation is about as follows: The strip is first submerged in a solution of about 10 per cent nitric acid and 2 per cent hydrofluoric acid by volume at a temperature of about 120°F. The time of immersion used is that which is sufficient to loosen or "rot" the scale. The strip is then washed with hot water and the scale scrubbed off in a stream of high-pressure water. Any scale adhering is removed by drawing the strip through fine abrasive wipers and the material given another water scrubbing. It is then ready for cold rolling.

The equipment used for cold-rolling stainless strip is much like that used in rolling carbon steel strip. Either a Steckel mill or a continuous roughing mill is used to effect all but a small portion of the reduction, the remaining portion often being made in a two-high mill because a better polish is accomplished by the large diameter rolls. If a continuous roughing mill is used, several passes through the stands will be needed with annealing and pickling operations between the passes. At one plant where three stands of four-high roughing rolls are used in tandem,[2] 10-in. stainless strip is reduced from 0.125 to 0.050 in. in thickness in two passes through the three stands. The strip is then

[1] PRENTISS, F. I., *Iron Age*, **129**, 777 (Mar. 31, 1932).
[2] SMITH, E. C., *Yearbook, Am. Iron Steel Inst.*, 185, 1932.

annealed, pickled, scrubbed, and returned to the mill. In making thin strip, the material is given three passes through the mill to a final thickness of 0.027 in., reannealed, processed, and given three more passes to a final thickness of 0.015 in. A final annealing, pickling, and scrubbing treatment prepares the strip for a polishing pass on a two-high finishing mill. It is then ready for final inspection and shipment.

Sheets.—The stainless steels commonly made into sheets comprise four general groups, each having various carbon contents:

1. Low chromium (10 to 14 per cent).
2. Medium chromium (16 to 30 per cent).
3. Chrome-nickel (18-8).
4. Chrome-nickel plus other alloy additions.

These alloys in sheet form are used for definite purposes. The first three groups are used to withstand atmospheric corrosion, the second and third groups to withstand corrosion of liquids, and the last three groups to withstand scaling at elevated temperatures.

Before rolling blooms or slabs of these steels into sheet bar, they must be carefully chipped and ground to remove all defects. Heating furnaces to heat the slabs for rolling must be kept free from dirt and must be maintained with a slightly reducing atmosphere to minimize scaling. Heating times are about twice as long as those for carbon steels. For tonnage production, a bar mill or universal mill is generally used to roll the sheet bar; but for smaller lots, plates are rolled on a jobbing mill and cut up into sheet bar sizes. The rolling procedure is about the same as that given for stainless plate. The plates are flattened while hot and sheared into sheet bars while still warm because they are usually less brittle than when cold. The sheet bar is pickled in 10 per cent H_2SO_4 at 150°F. and ground free from any defects. Sandblasting is sometimes used to remove the scale, followed by a light pickle to show up any defects.

The rolling of the sheet is carried out by the same pack methods used for carbon steel sheets, except that hand manipulation is the most common method. The production is about one-third that obtained on carbon steel sheets, owing to the limited number of passes that can be taken without reheating and the fact that the

reduction per pass is limited to about 15 per cent, as against 25 per cent for carbon steel. The ranges of temperature within which the sheets can be rolled are narrow if the sheets are not to be damaged. Average figures are about as follows:[1]

	Starting temperature, °F.	Finishing temperature, °F.
Group 1	1500	1200
Group 2:		
16% Cr	1500	1200
30% Cr	1800	1500
Group 3	1850	1650
Group 4	2000	1800

The operation of rolling stainless sheet is an art and a highly trained and intelligent crew is necessary if good results are to be obtained.

It is usually necessary to heat-treat the hot-rolled sheets. The straight chromium steel containing less than 0.12 per cent carbon may be air-cooled from the annealing temperature (1400 to 1550°F.) and is, therefore, treated in a continuous furnace. When the carbon is above this figure, it is necessary to box-anneal them and cool them slowly to avoid hardening. The 18 per cent chromium, 8 per cent nickel alloy is heated to about 1900°F., the lighter gauges (18 gauge and lighter) being air-cooled and the heavier gauges being water-quenched. The complex alloys of group 4 may or may not be annealed, depending upon their use and methods of fabrication. If annealed, the annealing temperature is usually at least 1900°F.

A scale is formed in the foregoing treatment which is difficult to remove. The sheets are usually pickled in a 10 to 15 per cent H_2SO_4 and 5 to 25 per cent HCl solution at about 165°F. They are then washed, scrubbed, and pickled in a milder solution of 10 per cent HNO_3 plus 1.5 per cent HF at about 130°F. It is essential to finish with a dip in dilute nitric acid to passify the surface, *i.e.*, render it more corrosion resistant.

A considerable tonnage of the stainless sheets produced is used for decorative work and for this purpose they must be highly

[1] JOHNSON and SERGESON, *Metal Progress*, **22**, No. 4, 21 (1932).

polished. The sheets are reduced one or more gauges in a four-high cold-rolling mill, reannealed, pickled, cold-rolled for polish on a two-high mill, and leveled. A mirror finish can be obtained in this way.

Protective Coatings.—Protective coatings as applied to sheet steel may be divided into two classes: nonmetallic and metallic. Under nonmetallic coatings come such processing as oiling, which merely provides temporary protection during shipping or storing; bluing, an oxide coating produced by passing steam into the annealing box during the cooling cycle, which provides varying degrees of indoor protection; and painting, which provides protection that is dependent upon the grade of paint, the corrosive conditions, and the maintenance.

The metallic coatings, such as zinc on galvanized sheet, tin on tin plate, and terne mixture on terneplate, will be described in some detail.

Galvanizing.—Of the various types of protective coatings applied to sheets to prevent corrosion and destruction by atmospheric agencies, zinc is the most extensively used because it is the cheapest metal available for the purpose. When properly applied it will give a very satisfactory coating. The process is called "galvanizing" and the product is known as "galvanized sheet." The crystallization effect that the zinc coating assumes on cooling after galvanizing is known as a "spangle," (Fig. 18-XII). The process consists essentially in preparing the surface of the sheet, immersing it in a bath of molten zinc for a time sufficient for it to acquire a coat, removing the sheet, and running it through a pair of rolls which smooth out the coating and remove the excess zinc. The zinc alloys with the iron, producing a very tight coating—one that will stand considerable distortion without cracking.

The classification of galvanized sheets is according to the weight of coating and the intended use. The amount of galvanizing on sheets is the total coating, expressed in ounces, on both sides of a sheet 1 ft. square. The weights of zinc coatings as applied by the hot-dip process are specified in five classes according to their use and according to the gauge of the sheet. For complete information on galvanized sheet specifications the following is recommended: Standard Specifications for Zinc-coated (Galvanized) Iron or Steel Sheets, *A.S.T.M. Designation* A93-27,

American Society Testing Materials, Standards, Part I, Metals, 287–392 (1936).

The hot-dip galvanizing practice starts at the end of the sheet mill practice. The sheets when received at the galvanizer are cold-rolled, thoroughly annealed, and sheared to the proper width and length. Following this, the sheets are thoroughly pickled and washed to obtain an absolutely clean surface. In some plants the sheets are then immersed in a tank of water where they

FIG. 18-XII.—Surface of frosty-spangle galvanized sheet, actual size. (*Courtesy of Carnegie-Illinois Steel Corp.*)

are kept until ready for galvanizing. This aids in the complete removal of acid and allows any gases such as absorbed hydrogen to escape slowly.

The galvanizing is done in an apparatus that is practically continuous in operation. It consists of a rectangular tank or kettle for holding the molten zinc ("spelter," as it is called) supported over a furnace setting for heating the spelter and a galvanizing machine which is placed in the kettle and draws the sheets through the molten bath. The tank is constructed of low carbon, basic open-hearth steel and, on the average, ranges in size to a maximum of 15 ft. long, 6 ft. wide, and from 3 to 5 ft. in

depth. It is usually coal- or gas-fired. The galvanizing machine or *rigging*, as it is called, consists essentially of three pairs of rolls, a flux box, and a frame upon which this equipment is supported. The first pair of rolls are inclined at an angle and feed the sheet down through the flux box, which is a rectangular box extending the width of the kettle at the entering end and open at both the top and the bottom. A second pair of rolls set in a vertical plane are placed at the center of the bottom of the tank, while a third pair is mounted horizontally at the other end of the tank, at about the level of the zinc. Guides between the rolls prevent the sheets from getting off their course while passing through the tank.

Figure 19-XII shows a diagram of the sequence of processes of a typical sheet galvanizing plant.

With the galvanizing machine in place in the kettle, the flux box extends half in and half out of the molten spelter and is filled with sal ammoniac (ammonium chloride) which fuses and floats on the spelter, thus remaining in the box. A sheet is brought from the wash tank and immersed for a few seconds in a bath of muriatic acid (a commercial grade of HCl). This acid treatment removes any rust that may have formed during the soaking period. The sheet is removed and fed into the

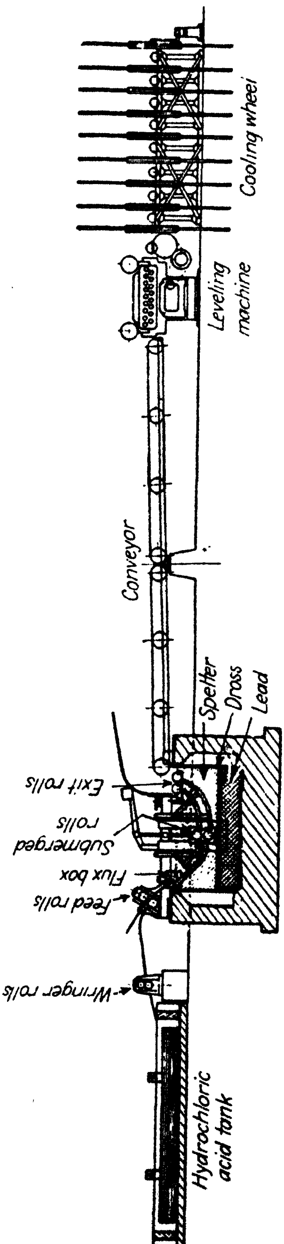


FIG 19-XII.—Diagram showing the sequence of processes from acid tank to cooling wheel. (*After Wallace G. Imhoff.*)

entering pair of rolls which force it down through the flux and under the surface of the molten zinc. The flux removes the film of water and acid out of contact with air and thus gives the sheet its final preparation for the galvanizing operation. The sheet is curved by the guides and entered into the center pair of rolls which in turn force it on through the bath. Guides force the front end of the sheet upward and enter it into the pair of exit rolls. During its passage through the hot bath, the sheet is gradually heated to the bath temperature where the alloying of the zinc and iron takes place rapidly. The speed of travel of the sheet through the bath (40 to 70 ft. per min.) is regulated so that the sheet is withdrawn by the exit rolls as soon as the alloying action has started enough to give a good bond. The exit rolls are kept covered with a thin even film of zinc and regulate the thickness of the coat which the sheet retains. These rolls smooth out irregularities in the coat and squeeze off the excess zinc. From the exit rolls, a guide bends the sheet forward so that it falls upon a conveyer which feeds it through a roller leveler to a cooling rack where the sheets are cooled in air to room temperature.

One of the greatest losses of zinc in the galvanizing process is in the formation of dross. Dross is an alloy of iron and zinc containing from 3 to 7 per cent of iron and is of a pasty consistency at the temperature of the molten spelter. This dross is very brittle when cold and ruins the surface of the sheet if it comes in contact with it. The dross is heavier than the zinc and sinks to the bottom unless convection currents in the spelter keep it in suspension. Proper firing methods can prevent this condition.

Various methods are advocated for cutting down the amount of dross formed, the principal one being the use of neutral fluxes. When the sheet is removed from the muriatic acid bath, it retains a film of a solution of iron salts on it because the acid attacks the sheet. The iron in this solution combines with zinc to produce dross. One method of reducing the amount of dross formed is to use a slightly acidified solution of zinc chloride in place of the muriatic acid bath and zinc ammonium chloride in place of the ammonium chloride in the flux box. This combination minimizes the amount of zinc-soluble iron salts entering the galvanizing machine with the sheets.

Tinning.—Tinning is the operation of coating metals with a thin film of metallic tin. The function of tin coating is to produce an excellent appearance and corrosion resistance. It also facilitates soldering. The present process of tin-coating base metal or black iron sheets is very similar to the procedure used in galvanizing. It consists in automatically passing individual sheets, which have been cleaned and pickled, through a tinning bath, then through a palm oil bath to protect and properly distribute the tin coating, and finally through cleaners which remove the excess palm oil and to some extent polish the sheet.

Some typical sequences of treatment which the base metal might follow in becoming tin plate are as follows:

Hot-roll treatment:

1. Hot-roll, black-pickle, black-anneal, cold-roll (usually 3 passes), white-anneal, white-pickle, tin.

2. Hot-roll, normalize, black-pickle, dry, cold-roll, white-anneal, white-pickle, tin.

Cold-roll treatment (coils):

1. Cold-reduce, clean, black-anneal (coil), cold-roll (temper), shear, white-anneal, white-pickle, tin.

2. If the coils are sheared following cold reduction, they will follow a sequence as in 1, with the exception of the shear.

Tin plate is produced with different amounts of tin coating. The grades carrying the least amount of tin coating are known as "coke plates" while those carrying the most coating are known as "charcoal plates." This terminology originated in the early days of the tin-plate industry and came about through the fact that the better grades of tin plate, those containing the heavier coatings, were made with base plates of charcoal iron and the cheaper grades with base plates made of coke iron. At the present time, however, all tin plate is made from steel whose carbon content is approximately 0.12 and under, so that the original significance has been lost. However, the terms "coke" and "charcoal" still designate a difference in the amounts of tin coating.

Tin plate is always sold on the basis of standards for the several coatings and not on the basis of the actual weight of coating. The tin coating varies according to the grade and somewhat upon the gauge. In the coke grades, which constitute most of the plate produced, the coating varies from about 1.25

to 2.25 lb. per base box; and from about 2.25 to 7.00 lb. per base box in the charcoal grades.

The term "base box" is a unit of measure of tin plate. The weight in pounds of a base box, known as the "base weight," is equivalent to the weight of 112 sheets of 14 by 20 in., or 31,360 sq. in. of any size.

Tinning Coke Plate.—The tinning apparatus (Fig. 20-XII) for "cokes" consists of a rectangular-shaped tinning pot which is wider than it is long, with a steel partition in the center running the width of the pot. A slit in this partition running horizontally and near the bottom forms the only connection between the two chambers. The pot is filled with molten tin to about 6 in.

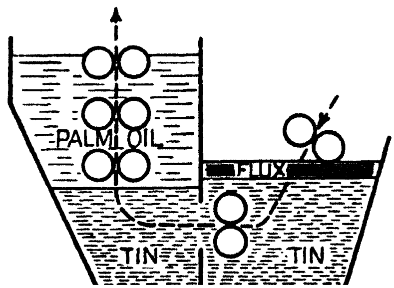


FIG. 20-XII. —Cross-sectional diagram of a tin pot.

above the slit and a flux box containing zinc and ammonium chlorides placed in the entering chamber. The other chamber is built up higher than the first and palm oil is placed on top of the tin in this chamber. A pair of rolls are placed in this oil just above the surface of the tin and another pair above them just at the surface of the oil. A third pair of rolls receive the plate from the finishing rolls and deposit it upon a conveyer.

In operation, a mechanical feeder thrusts a plate down through the flux box and into the tin where guides conduct the front end of the plate through the slit and up to the first pair of rolls. The tinning is done during this period and the speed of travel determines the extent of alloying of the tin and iron. The first pair of rolls grip the plate, strip the excess tin from it, and deliver it to the finishing rolls which smooth out the plate while still in the hot oil. The delivery rolls deposit the plate on a conveyer which carries it directly to several pairs of cleaning rolls in tandem which remove the oil from the plate and polish it. These rolls

are made up of flannel disks; bran is generally used as a scrubbing medium to absorb the oil. The cleaned plates are mechanically stacked as they come from the cleaners.

The flux of zinc and ammonium chlorides in the entering chamber has as its purpose the thorough cleaning of the black sheet surfaces, the removal of the moisture, and the surface preparation so that the tin will adhere uniformly.

The palm oil used in the exit compartment serves as a medium in which to keep the tin molten on the sheet while passing through the rolls. This produces a better tin distribution and aids in the removal of excess tin. It also aids in protecting the tin from oxidation or discoloration while cooling.

The weight of coating produced depends largely upon the pressure exerted by the rolls in the oil bath. Temperature of the bath and the rate of travel through the machine will also be factors. The surface condition of the sheet will also be a factor, as roughness or overpickling will result in undue amounts of tin being retained on the sheet.

Tinning Charcoal Plate.—The tinning of charcoal plate, which demands the application of heavier coatings, is normally produced by the commercial tinning machine as described for coke plate. Following this, they are hand-dipped in a tin bath held at a low temperature to aid the adherence of the tin and then into a palm oil bath in which the rolls distribute and regulate the coating thickness according to the weight or grade of plate desired.

To produce heavy tin coatings on such objects as kitchen utensils, pails, and milk cans, the products are fabricated from black plate before tinning. After suitable cleaning, the objects are dipped repeatedly in tin pots until they obtain the desired coating. The excess is either removed by draining, by the aid of a blowpipe, or is hand-wiped.

Inspection, Assorting, Reckoning, Weighing, Boxing.—After tinning and cleaning, both the coke and charcoal plate follow a similar procedure. They are taken directly to the assorting tables where they are inspected on both sides for defects and assorted into proper weights.

Tin plate is classified at the mill as follows: Sheets that have no visible base plate or coating defects and are full size and commercially flat are termed "primes"; those with minor imperfec-

tions in the base plate, in the coating, in the shape or size are "seconds"; those which are poorly tinned or which can be made salable by recleaning and retinning are termed "menders"; while those sheets which have prohibitive defects are termed "wasters." This latter group are usually detinned, although frequently some portions of the sheet may be salvaged and sold at a reduced price.

Defects in sheets are due to a great many causes. It should be first noted, however, that the production of perfect tin plate is impossible, *i.e.*, with an absolutely continuous coating with no breaks or apertures, however small. This is due to the existance of minute pinholes in the coating but, when they are so small as to be invisible to the naked eye, they do not affect the commercial utility of the tin plate and hence may be disregarded.

The usual defects that cause an imperfect sheet can generally be traced to one of the many operations through which it has passed. Defective base plate may be due to an original badly cast ingot, blisters, scale pits, roll marks, pinchers, scratches, overetching in pickling, lapping in cold rolling, etc. Sometimes the size and shape are not accurate, *i.e.*, the sheets may be short, have rounded corners, or rough edges. The sheets may be warped or bowed as a result of too hot a tin bath. The sheets may have coating imperfections such as dirt in the steel or rolled into the surface, preventing tinning; black patches of oxide due to improper pickling; grease spots which may cause portions of the sheet to be untinned; a yellow discoloration, the result of permitting the palm oil to get too hot. The tinned plate may become dirty, badly scratched, or be incompletely cleaned.

The inspected and classified sheets are then "reckoned," *i.e.*, the proper number of sheets are counted into packs of 112, which constitute a standard package. Tin plate may also be packed 56 or 224 sheets to the package depending upon the base weight and size. These packages may be properly packed for protection and marketed as such, or 10 such packs may be combined to make a bundle for shipping.

Terneplate.—Terneplate differs from tin plate only in the constitution of the coating, which is a lead-tin alloy instead of a pure tin. The alloy used for terneplate usually contains about 12 to 25 per cent tin and 88 to 75 per cent lead. The tin content is necessary to make a continuous coating and produce the proper soldering characteristics. Since lead does not form an inter-

metallic compound with iron, the tin present will form a compound with the iron and make an adherent base for the alloy.

There are two general classifications of terneplate: short ternes and long ternes. The short ternes are made in sizes and gauges comparable to tin plate, while long ternes are large sheets more comparable to galvanized sizes.

The classification of ternes is according to the weight of the coating and the weight or gauge of the base metal. Short ternes have the same base weights as tin plate, except that sheet lighter than 0.107 in. (31 gauge) or 100 lb. per base box or heavier than 0.0214 in. (25 gauge) or 195 lb. per base box is rarely specified.

Coatings on short ternes are specified in terms of pounds per double base box. This means that they are figured on the basis of 112 sheets 20 by 28 in. instead of 112 sheets 20 by 14 in. as with tin plate. Manufacturing ternes are those sheets with 8 lb. or less of coating per double base box. Roofing ternes are those with coatings ranging from 15 to 40 lb.

Long ternes usually carry coatings of 8 lb. or less per double base box; however, for special requirements this may range from 12 to 15 lb. Since most of this material is used for fairly heavy manufacturing purposes, the base metal gauges are usually very heavy in comparison to tin plate gauges, ranging from 30 to 14 gauge.

Short Ternes.—The preparation of the base metal for short ternes is almost the same as that for tinning. Plate produced by the continuous mills as well as that produced by pack rolling is used. The chief divergence in the processing is that the black plate receives a much lighter cold finish rolling treatment than tin plate receives. This is due to the fact that a highly polished surface would not satisfactorily hold the heavier coating. Specifications for composition of the base plate may differ somewhat from tin plate, depending upon the ultimate use of the product.

The method used in applying the coating to short ternes depends upon the weight of the coating and other characteristics of the grade being made. For application of the lighter coatings, 8 lb. and less, the apparatus is similar to that used in coating tin plate, with the exception that a terne mixture is used instead of the tin bath. The black plate passes through a flux of zinc chloride, then through the molten terne, held at a temperature

somewhat higher than the tin bath (700 to 725°F.), and leaves the machine through a hot palm oil bath.

For heavier terne coatings a combination of machine coating followed by hand dipping is used. Since sheets carrying these heavier coatings are used for roofing, they are resquared before coating, as accurate dimensions and fully protected edges are essential in this application.

If an oil finish is desired, as in plate for roofing or deep drawing, the plates are ready to be inspected and packed as they come from the terne coating machine or final palm oil bath if hand-dipped. If a dry finish is specified, as in light-coated manufacturing ternes used to make containers, the plates are cleaned on the same machines as are used in cleaning tin plate. The cleaning mixture usually consists of peanut shells and sawdust or some similar oil absorbent, instead of bran. This is an economy measure, as terne coating contains lead; hence the use of bran with its subsequent sale as stock food cannot be realized.

Short ternes are assorted and packed in the same fashion as described in handling tin plate. There is the difference, however, that there is no sale for seconds in the plate with coatings heavier than 8 lb.; hence defective sheets in this classification are run through a terne-coating machine where the excess metal is removed and the resultant product reassorted for prime manufacturing ternes.

Long Ternes.—Long terne sheets are automatically coated with terne mixture in the same general manner as in machine-coating short ternes and coke tin plate. Hand dipping is seldom necessary as heavy coatings are not often produced in these sizes.

The cleaning, inspection, and assorting of long ternes follow the same procedure as described for short ternes. After cleaning, the dry-finish long ternes are assorted and packed, but to secure an oil finish the sheets are then passed through rolls saturated with oil. Terneplate is assorted into primes, seconds, wasters, menders, and scrap.

Mottle.—One of the characteristic features of heavily coated terneplates is the "mottle" or grained areas appearing over the surface as the result of the crystallization of the coating on cooling (Fig. 21-XII). The size of the mottle is controlled mainly

by varying the cooling rate and is varied according to the specifications of the customer. The lines dividing the grained areas vary in thickness with the weight of the coating.

General Application of Sheet Steel Products.—The various grades and finishes of strip steel, sheet steel, galvanized sheet, tin plate, and terneplate are used for such a multitude of purposes that any detailed description of these uses would entail

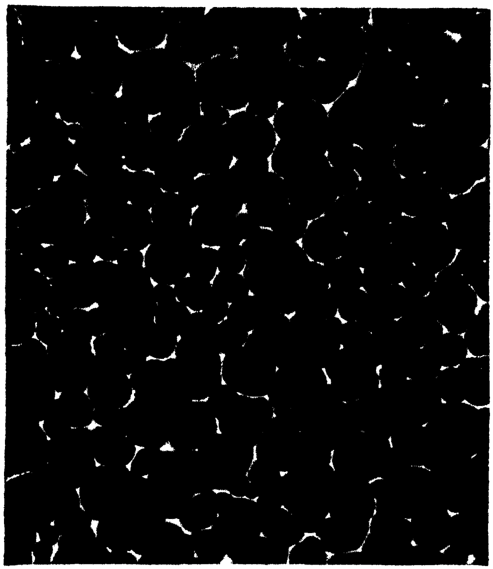


FIG. 21-XII.—Surface of a 40-lb. terne sheet, actual size. (*Courtesy of Carnegie-Illinois Steel Corp.*)

volumes. The following discussion on the applications of this field of products is made merely to show the broad coverage.

Sheet and Strip Steel.—Agricultural implements, auto accessories and in general automobile construction, shipbuilding, building and construction materials (hardware, trim, and other fabricated sections), electrical equipment, enameled articles, furniture and stoves, machinery parts, metal containers, railroads (cars and locomotives), pressed and formed articles, etc.

Galvanized Sheet.—Corrugated roofing, culverts, siding sheets, gutters, furnace casings, ventilating ducts, tanks, buckets, pans, etc.

Tin Plate.—All types of containers for foodstuffs, kitchen utensils, merchandising displays, toys and novelties, seals, tags, signs, etc.

Terneplate.—Roofing, ventilators and hoods carrying corrosive gases, automobile gasoline tanks, metal furniture, oil cans, various nonfood containers, etc.

Suggested Questions for Study and Class Discussion

1. Make a flow diagram showing the processing of a sheet to be used in drawing an automobile fender by the pack-roll method.

2. Make a flow diagram showing the processing of a sheet to be used in drawing an automobile fender by continuous methods.

3. What reasons could you advance for the trend taken to replace the pack-roll method of producing sheet by the continuous mills?

4. Discuss the possibilities of producing strip by direct rolling from molten metal, *i.e.*, pouring molten metal through water-cooled rolls, properly adjusted, with strip evolving from the exit end.

5. Why do the wide continuous strip mills not roll directly to the gauge desired?

6. What is the purpose of cold rolling of strip?

7. Describe the processing you might use in producing high carbon strip for razor blades.

8. What type of coated sheet would you use in the following applications: coffee cans, paint cans, beer cans, oil cans, siding, roofing, milk cans, gasoline tanks, bottle caps, culverts, refrigerator cabinets, stoves?

9. What typical uses can you list for stainless sheets?

CHAPTER XIII

THE MANUFACTURE OF STEEL WIRE

Steel wire in its many forms, shapes, and sizes has widely varying applications ranging from its spectacular use in the cables of a suspension bridge to its prosaic use in the form of common pins. It is furnished in practically every kind of steel and in sizes varying from about the thickness of a human hair to where it merges into the classification of steel bars. Wire can be had in various finishes, ranging from a dull dark finish to a high polish, including various coatings such as zinc and tin, and in a wide range of physical properties brought about by regulation of the chemical composition and degree of the final cold-drawing. One thinks of wire as being round, but in addition to this shape, it is furnished in many others, such as square, hexagonal, or half-round. Since the methods used in producing these special shapes are essentially the same as those used for round wire, the present discussion will be limited to the consideration of wire of round cross section. The relation of gauge number to diameter of round wire is given in Table 1-XII.

The essential steps in the manufacture of wire consist in rolling billets to one of a number of standard sizes of wire rod, which are coiled directly from the finishing stand of the rod mill. These coils are heat-treated, if necessary, and then pickled, washed, and coated with any one or a combination of several materials to aid in the drawing operation. The coating is baked on at a low temperature, and the rod drawn through a single die or succession of dies to increase its length and decrease its diameter by the required amount. The procedure will be discussed in greater detail in the following pages.

Rolling the Wire Rod.—Several different types of rod mills are in use at the present time. Probably the most important is the continuous mill which can roll one, two, or four rods at once, depending upon the design, two at a time being the most common. These mills usually consist of about 18 two-high stands arranged

in tandem, the eight stands composing the roughing set being placed close together but separated by a short roller table from the 10 stands of the finishing set which are spaced more closely together than the stands of the roughing set. The diameters of the pairs of rolls are decreased and/or their speeds increased enough in successive stands to take up the slack and maintain a small but controlled tension on the rod during rolling. One mill of this type is driven by a single 4,500-hp. motor, the speed of each stand being fixed by a gear set. This mill is capable of rolling No. 5 rod (0.207 in. diameter) from 2 by 2-in. billets, 30 ft. long, the maximum diameter of rod that can be rolled being 5/16 in.

In rolling the wire rod, the greatest single difficulty encountered is in getting the billet completely rolled before it becomes too cold. Since the rods are very small, high-speed operation is required in order to keep the rod uniform in size. For this reason, the continuous furnace that furnishes the mill with hot billets is usually of the side discharge type having a ram which pushes the end of the billet directly to the first roughing stand which is rarely more than 2 or 3 ft. from the furnace. In this way, the front end of the billet, in the form of wire rod, is finished and coiling before two-thirds of the billet is out of the furnace; the finishing temperature is kept uniform throughout the rod and the diameter of the finished rod is therefore uniform over its entire length. The reduction is usually accomplished by alternate diamond and square passes in the roughing and intermediate rolls and by alternate oval and square in the later passes. The final pass is always round and of very accurate dimensions. Twisting guides are employed to turn the piece between passes when necessary. The speed of delivery of the mill may be as high as 4,000 ft. per min. Tubes serve as delivery guides from the finishing stand and lead the rods to the automatic coilers, two or three of which are provided for each strand of rod that the mill is designed to roll simultaneously.

Two disadvantages of the continuous mill are that, at the high speeds, the tension in the rod is difficult to control within close limits and, when rolling two or more strands at once, it is impossible to compensate for differences in temperatures between the rods by adjusting the rolls. Most of the defects encountered in continuous rod are due to variations in rod

tension. It is also obvious that, in any given pass, the hotter the rod the more nearly it will approach the desired dimensions upon issuing from that pass. When only one strand is being rolled at once, slight irregularities in temperature can be compensated by adjusting the rolls in the finishing passes. When two rods at different temperatures are in the same stand at once, such adjustment cannot be made.

These difficulties are surmounted in various ways. In one mill, the first 12 stands are set close together and are carefully controlled with regard to speed and draft. Following the twelfth stand a looping table is provided where the two strands being rolled at once are given a small loop to remove the tension before entering the next stand in the tandem set. The thirteenth and fourteenth stands are driven by a separate motor. The first 12 stands are driven by a single motor and, owing to the lower speeds in these stands, the control is quite accurate. In order to get good control of draft and speed in the finishing passes, a separate set of stands is provided for each rod, the two rods being divided after the fourteenth stand. The two finishing sets consist of six 9-in. stands each and are separately driven. In this way, each rod can be separately controlled through the finishing passes. Another method consists in having the intermediate and finishing set split into groups. The roughing set of eight stands and the first four intermediate stands are set in tandem with about 15 ft. between the eighth and ninth stands to allow some slack and are all driven by a single motor. A group of two stands in tandem is placed parallel to the intermediate stands and driven in the opposite direction from the four intermediates, repeaters being used to convey the rods through the 180-deg. loop. The four final stands in tandem arrangement are placed parallel to the preceding two and repeaters again used to effect the 180-deg. loop. The tension is relieved between the groups, and more flexible speed adjustment is possible with separately driven groups. The speeds of the groups are so adjusted that the loops do not grow in size after being formed and the cooling is therefore uniform for each unit of material going through the loop. Nonuniformity in temperature from billet to billet and from one end of a billet to the other is being rapidly minimized by the recent advances in continuous furnace design, operation, and methods of automatic temperature control.

As stated above, the finished rods are delivered to the coilers through tube guides and coiled on revolving reels which collapse when the rod is completely wound on it, thus allowing the bundle resulting from one billet to be automatically discharged to a conveyer (usually of the hook type) which conveys it away from the mill. The temperature at which the finished rod is coiled has a considerable effect on the grain size of the cold coil as the material cools much more slowly in coiled form than in a single strand. In order that the internal structure may be uniform from coil to coil it is necessary to regulate the coiling temperature and thus overcome irregularities in finishing temperature. The tubes through which the rods pass on their way to the coilers are often sprayed with water, the amount of spraying being dependent upon the desired amount of cooling.

After reeling, the coils are conveyed along a trough out of the reeling pit to a point where they are automatically picked up by a continuous hook conveyer; this conveyer advances slowly allowing time for the rods to cool. Just before the rods are inspected, the front and back ends of each coil are removed by a shear. The amount sheared depends upon the condition of the rod as these ends are usually off gauge or finned.

Inspection.—The type and extent of rod inspection are dependent upon the order specification. There are standard practices requiring certain tests for specific grades of steel where defects are most likely to occur, while in other cases, the customer may specify special tests. All coils are checked for size, section, and surface defects. Additional tests may be made, such as the twist test, which consists in twisting a piece a predetermined number of times in one direction and then back in the opposite direction, to disclose laps and seams; the etch test using an acid to show the position of the ingot pattern, center porosity, segregation, and pipe; the nick-and-break test, where a test piece is broken and the fracture examined to disclosé pipe; and the tensile test to check the strength properties.

The principal rod defects are as follows:

1. Mill defects.

2. Torn surface, heavy scale, heavy grease, light bundles, badly tangled coils, visible laps, scratches, flat spots, off size, overfill, underfill, finned ends, and size variation between front and back ends of coil.

3. Steel defects.
4. Pipe, slivers, seams, and lapped billets.

Processing Preparatory to Drawing.—The coiled wire rod on the conveyer cools slowly enough to form the two previously mentioned structural constituents: pearlite and ferrite. As the carbon content increases, the amount of pearlite increases until at 0.85 per cent carbon the steel consists entirely of pearlite. This constituent is made up of alternate thin plates of alpha iron and the very hard and brittle intermetallic compound Fe_3C. The structure of pearlite is such that it hardens so rapidly upon cold working that very little cold work can be done upon it. Also, a process anneal will not entirely relieve the distortion produced in it by the cold work.

Steel in the fully annealed condition, therefore, contains a constituent that draws quite readily (ferrite) and one that cold-draws hardly at all. The best drawing properties are obtained from a metal or alloy when the constituent or constituents of which it is made draw equally well throughout the material. It is obvious that the fully annealed structure referred to above does not fulfill this condition. Steels very low in carbon contain such a small amount of pearlite that it is not noticeably detrimental to the cold-working properties of the metal. The best cold-working properties are obtained from low carbon steels, however, by replacing the patches of pearlite with small round particles of ferric carbide (called cementite) imbedded in the ferrite matrix. These round particles offer much less obstruction to the flow of the ferrite than the very much larger plates of the same composition that form part of the pearlite. This change can be brought about by giving the rod a process anneal, *i.e.*, annealing the material below its lower critical temperature which causes the plates to break up into the fine particles.

High carbon steel rod (over 0.30 per cent carbon) in the annealed condition contains so much pearlite that the material would work-harden very rapidly unless some heat-treatment is given it that will increase its plasticity. The treatment used to bring about increased plasticity in high carbon spring and rope wire or rods is known as "patent annealing." In addition to the primary purpose, patent annealing also has as its objective the production of a uniform structure with the best combination of strength and toughness. The treatment consists in

heating the material to above the upper critical temperature and then cooling in either air or molten lead. This variation in cooling practice controls the tensile strength and grain structure to a certain extent.

The patenting operation is continuous with the coils being placed on reels at one end of the furnace, led around sheaves and through the furnace. The strands after passing through the lead pan or the air are wound on reels at the discharge end. These reels are driven by a single motor driving a line shaft, which is connected to each reel.

The desired characteristics are obtained by varying the reel speed, furnace temperature, and the method of cooling. When lead quenching, the furnace temperature at the exit end ranges from 1650 to 1750°F., and the lead pan varies from 850 to 950°F. Reel speeds vary from 15.5 ft. per min. on sizes ¼ in. and over to 36.5 ft. per min. on 13-gauge wire. Air-cooled stock uses the same speed range but the temperature at the exit end of the furnace is higher, ranging from 1800 to 1850°F. These are general figures and will vary with different plant setups.

In discussing the foregoing treatments, the influence of grain size on the cold-drawing properties should not be overlooked. Large grains make for weakness in the material and a steel of small grain size draws better than one of large grain size. The grain size can be controlled by properly adjusting the time at heating temperature and the rate of cooling after processing. The weakening effect of large grains in wire is particularly noticeable because the cross-sectional area of the wire is so small. Low carbon rod is seldom heat-treated while high carbon rod must be patented before drawing, if more than one or two drafts are to be made on it.

The next step in the preparation of the wire rod for drawing is cleaning, and it is a very important one because any scale adhering to the surface of the rod would score the surface of the die and ruin it for further use without redressing. The surface is cleaned by pickling in dilute sulfuric acid at temperatures ranging from 150 to 180°F., the chemistry and essentials of the method used being the same as in the case of sheets. A revolving crane is used to handle several coils of rod which are strung on a steel bar held by the yoke of the crane. Several vats for holding the steam-heated pickling solutions, a dilute pickling

solution, and fresh rinse water are arranged around the crane. The coils are immersed in the dilute pickling solution to remove most of the scale and finally are rinsed in fresh water. Any adhering scale is washed off with a high-pressure water spray.

The final step in preparing the rod for drawing is the application of a coating to aid in the drawing operation. In conjunction with the lubricants (if any) applied during drawing, the purpose of the coating is to neutralize any residual pickling acid and to aid in reducing the friction of the wire in passing through the die. The type of coating and the amount of coating applied depend upon the amount of drawing necessary to produce the final size, the finish desired, and the kind of steel being drawn. Two different methods of drawing are in use: wet drawing and dry drawing. Of these, the latter is the more important as most drawing operations are conducted by this method. In most cases wet drawing is a finishing operation designed to produce a special surface finish on the material and, as it is more expensive than dry drawing, special finish wires are seldom entirely drawn wet from the rod except in large sizes but are drawn nearly to size by the dry method and then drawn wet to the final gauge.

The coating for dry drawing usually consists in giving the rod a "sull" coat, followed by a coating of lime which is baked on at a low temperature. In producing the *sull coat*, the coils are removed from the rinse water and placed in a pit for some time where fine sprays of water are played on them. The action of the water, oxygen in the air, and perhaps traces of acid remaining from the pickling treatment produces a very thin surface coat of brown or greenish rust. This sull coat aids in lubrication and is quite necessary to dry-drawing operations when many drafts are to be taken. This coating darkens the surface, however, and cannot be used when bright finishes are to be produced on coarse wires. The thickness of the coat can be controlled by controlling the time of exposure to the oxidizing conditions and the temperature at which the treatment is carried out.

In dry drawing, the chief function of the coating is to act as a carrier and absorbent of the lubricant added to the die. An uncoated wire or rod would not retain enough lubricant, would wear the die away rapidly, and would require too much power for

economical drawing. A coating of slaked lime is the best material found for fulfilling these requirements. It is cheap and easy to apply and, besides acting as an aid in lubrication, it neutralizes any traces of acid remaining on the rod and protects it from further oxidation before and during drawing. The procedure used in lime coating consists in dipping the coils into a tank of slaked lime emulsion and leaving them there long enough to be thoroughly coated with it. The emulsion is made by adding dead burned lime, CaO, to water to form $Ca(OH)_2$ according to the reaction

$$CaO + H_2O = Ca(OH)_2$$

A part of the calcium hydroxide dissolves in the water while the remainder remains suspended in the solution as very fine particles, forming an emulsion. The tank is usually steam-heated in order to keep the contents at about 140°F. The amount of excess solid in the emulsion is regulated according to the thickness of the coating desired, which in turn depends upon the nature of the work to be done on the rod or wire. The coating must be dried or baked on before the material can be drawn. The wet coils are placed on buggies which are slowly propelled either by gravity or by pushers through a long low brick chamber. The operation is of the continuous type, the coils being heated to between 250 and 400°F. for a period ranging between 3 and 12 hr., depending upon the kind of material and the conditions prevailing. The baker is heated with hot air which is admitted through places in the floor and roof. In addition to the drying action, the baking treatment drives off any hydrogen that might have been absorbed during the pickling treatment. The coils of rod are usually left in the baker until required by the wire mill when they are taken out and drawn as soon as they have cooled to atmospheric temperature.

Coarse wires which require only one or two drafts from the rod but on which a bright finish is desired cannot be given a sull coat because it darkens the surface. Rod for such wires is cleaned, given a lime coat, and drawn to the finished size, thus producing a bright finish. When finer wires are desired, the ordinary bright finish is obtained by giving the rod a sull coat and a heavy lime coat before drawing, as the sull coat is necessary when extensive drafting is to be carried out without inter-

mediate annealing. Several drafts are required to produce even the ordinary finish on a sull-coated rod. When especially bright finishes are required on the finer sizes, the wire must be finished by wet-drawing methods.

Wiredrawing Equipment.—The *die* is really the crux of the wiredrawing process as a satisfactory product cannot be obtained from dies that are poorly designed, poorly finished, or not made of the correct material to perform the job required of them. In general, the wiredrawing die may be defined as a plate of some suitable material containing one or more tapered holes called "die holes." The shape of a typical die hole is shown in cross section in Fig. 1-XIII. The mouth is considerably larger than the entering material to afford room for the die lubricant which adheres to the surface of the material being drawn into the hole. The next tapered portion, called the "approach," is very accurately machined and polished and accomplishes the major portion of the reduction in cross-sectional area of the piece. The bearing section has only a very slight taper and is machined and highly polished. The exit end of this section must be very accurately made as it fixes the size and shape of the emerging wire. The relief section is countersunk to prevent a breaking away of the die metal at the end of the bearing section such as would occur if no relief section were present. The exact dimensions of the various sections of the hole as well as the tapers used depend upon the size of the material being drawn and its composition, upon the amount of draft to be taken, and upon the material of which the die is made. In designing and making these dies, care should be taken to see that the holes are accurately machined and polished so that the desired size and shape will be obtained and the surface of the emerging wire will be free from scratches or other die marks. The tapers of the approach and bearing sections must be so adjusted that the minimum amount of frictional resistance will be set up and the deformation will be equally spread over the entire cross section of the material being drawn and not concentrated at the surface.

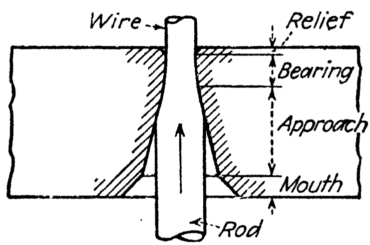


FIG. 1-XIII.—Cross section of a wiredrawing die.

In spite of the lubricants and coatings applied to the rod and wire, considerable frictional resistance is offered by the die to the passage of the material through it. Any material from which the die is made must possess, therefore, hardness and wear resistance in addition to freedom from internal flaws and sufficient strength to withstand the pulling action of the material being drawn through it. Dies are made of chilled cast iron, steel, tungsten carbide, and diamond, each type of material being, in general, best fitted for a certain type of work. Chilled cast-iron dies are made of white cast iron, usually containing special alloying elements, and are cast in metal molds with the rough holes in them. The inside surface of the hole, being chilled, is extremely hard and wear resistant. The body of the die must be made thick enough to withstand the pulling action during drawing. The rough holes in the die must be reamed out and finished. Dies for drawing the finer sizes contain more holes than those designed for the coarser sizes. Cast-iron dies are used in drawing the softer rods of maximum size of about 0.35 in. diameter and the harder rods of about 0.30-in. diameter. The minimum size drawn through these chilled iron dies is about 20 gauge because of the difficulty in reaming holes of smaller diameter in this material. After a die hole has been worn away to a size too large for further drawing of the gauge for which it was designed, it is reamed out for the next larger size.

Steel dies are made from a solid steel block that has been carefully made and fabricated by forging. The steel usually contains sufficient special alloying element to render it very hard and wear resistant after appropriate and carefully conducted heat-treatment. Cold hammering of the die is often resorted to in shaping it up in order to produce high hardness in the material. The die holes are punched in the block while the metal is hot and machined to the final shape and size after heat-treatment. Steel dies are used for drawing all special shapes other than round because reaming complicated sections in chilled cast iron is too difficult. All coarse wires are drawn through steel dies because of the greater strength of the steel in resisting the pulling action of drawing. These dies are also used in wet-drawing the finer sizes of wires.

The wearing away of steel and cast-iron dies during drawing is a serious drawback to their use, particularly on fine sizes where

the tolerances on dimensions are usually more rigid. The wearing away of the hole is progressive and large coils of drawn wire are smaller at the front end than at the end that is drawn last. The amount of wear depends upon many factors, principal among them being the hardness of the material being drawn, the perfection of the cleaning of the wire, the lubrication of the wire, and the amount of draft taken. Some tolerance must be allowed in the specifications because in drawing a 0.120-in. diameter wire through a chilled-iron die, it is usual to start with a hole 0.1195 in. and, on the average, the end of the bundle will come out about 0.1205 in. in diameter. A chilled-iron die will draw about 8,000 ft. of 0.120-in. diameter wire before it is worn out past the average allowable tolerance.

Since frequent replacement of dies is a costly procedure, *diamond* dies are often used when extreme accuracy and uniformity of section are necessary in finer sizes of wire. Diamond is the hardest substance known and is very wear resistant. Diamond dies are made by cementing a flat crystal of diamond in a metal disk and then working a hole of the desired size through it with special drills and diamond dust. These dies are very expensive because of the cost of the diamond and the difficulty in constructing the die, but they wear a long time and the cost of replacement is small if the diamond is properly supported in the metal so that it will not break under the pull. Within recent years the older types of dies have been superseded by a solid type of die composed of a forged steel casing holding a nib or carbide insert. The nibs, which are hard and extremely wear resistant, consist of one or more carbides (tungsten, tantalum, titanium, etc.) mixed with a bonding agent such as cobalt, pressed into the desired shape, heat-treated or sintered into a hardened rough form, and then mounted, sized, and polished. This type of die gives longer die life, more uniform size, and increased production. For example, where a chilled-iron die is able to draw only 8,000 ft. of 0.120-in. steel wire, a tungsten carbide die will usually draw 2,000,000 ft. or more of the same material within the size tolerances.

The mechanical setup for drawing the material through the die depends upon whether single or continuous drafting methods are used. These names are self-explanatory, single draft drawing meaning that the rod or wire is given only one draft and

recoiled, while in continuous drawing the wire or rod is given several drafts in different dies in succession before coiling. The equipment for single draft drawing consists of a long table, called a bench, upon which are mounted the die holders with a reel or "block" behind each. These blocks are powered either by individual motors or by shafts and gears from a single motor and arrangements provided for stopping, starting, and regulating the speed of each block independently. In addition, a drawout device is provided to draw enough of the wire through the die

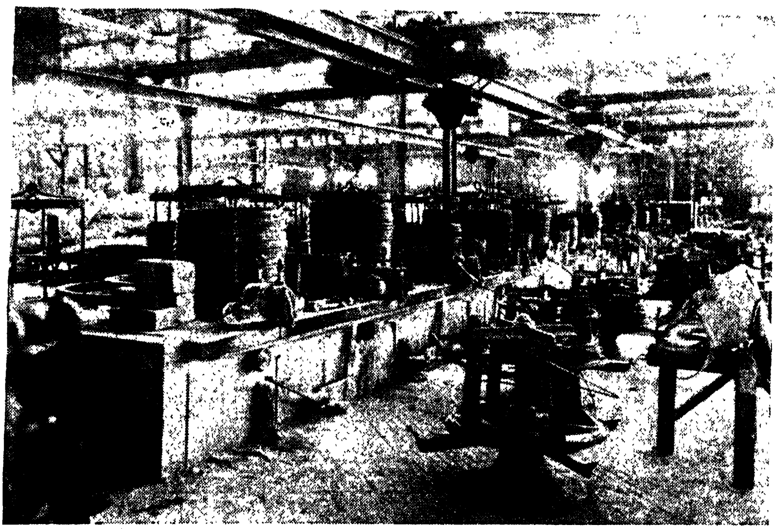


FIG. 2-XIII.—Wiredrawing frame. (*Courtesy of John A. Roebling's Sons Co.*)

so that it may be clamped to the block. An idler reel of some kind is placed on the floor in front of each die holder to hold the coil or rod while it is being drawn. A mechanical pointing device for decreasing the cross section of the front end of the coil enough so that it may be pushed through the die and grasped by the jaws of the power pull is usually a part of the equipment, although some are pointed by hand and others are so large that the end must be machined. The entire equipment described above is known as a *wiredrawing frame* (Fig. 2-XIII) and is built in several sizes, depending upon the work to be done upon it. Frames for giving the initial draft to the rod are very rugged in construction while those designed for drawing the finer sizes of wire are comparatively light. The diameter of the blocks

is usually taken as the size of the frame, a 22-in. block being almost the only one used for drawing wire down to 15 gauge. Smaller blocks, down to about 8 in. in diameter, are used for the finer sizes.

In continuous wiredrawing machines, the various dies cannot be placed close together and the entire drawing operation actuated by a pull on the section emerging from the last die because the strain is too great for the small cross section to withstand. To overcome this difficulty, a power-driven block is placed after each die and the wire wrapped around each block several times so that the material is pulled through each die by its own block. Each succeeding block must, therefore, be driven enough faster than its predecessor to take up the slack, but no more, or slippage of the wire on the blocks will occur which is detrimental to the surface of the wire. Separate motors are provided for each block in many cases and arranged so that the speed varies with the load, thus minimizing slippage. The continuous method has the advantage of greater production from a given number of blocks because it does away with the time and expense necessarily involved in handling the coils between drafts. The mechanical features necessary in distributing the speeds of the various blocks are expensive and not always entirely satisfactory, however, and the single draft method is still preferred in many places in drawing the coarser sizes. The continuous method is nearly standard practice in wet-drawing the fine sizes.

Wiredrawing Operations.—In dry-drawing the rod or wire, the proper die is placed in the die holder and the space provided on the entering side filled with die lubricant. This material is necessary to prevent excessive heating and wearing of the die and to produce a wire of uniform section free from surface scratches and other defects. It is placed on the entering side of the die so that the material being drawn must pass through it, become thoroughly coated with it and continually mix the lubricant. The lubricants used vary considerably with the type of work being done, the kind of steel being drawn, and the finish desired, but the most generally used lubricants include specially prepared greases, tallow, pulverized soap, and oil mixed with flour. As soon as the wire rod has been given one draft, it is known as wire and if it is not in a finished state it is generally called "process wire."

In beginning the wiredrawing operation, the bundle of coated and baked rod is placed on the holder provided for it, the end of the coil pointed and threaded through the die. The threaded end is grasped by the power puller and enough wire drawn through for it to be clamped to the block. The block is then started and run at a desirable rate of speed until the coil is drawn, when the block stops automatically. The coil of wire is then removed from the block either by hand or by crane. The procedure in continuous drawing can be easily inferred from the above. One application of coating and lubricant will last for several drafts, but for many drafts either a very heavy hot lime coat must be used or the wire must be treated twice. The speed of the operation is limited by the heat generated by friction at the die. This speed may be increased by the use of water-cooled dies. The number of drafts that can be given the material before it becomes so hard and brittle that it will break on further drawing is dependent upon the kind of steel, the treatment of the rod before drawing and the amount of reduction taken in each draft. For example, a rod can be given three drafts, each of 20 per cent reduction in area but it will not stand a single draft of 60 per cent.

The coarser sizes of low carbon wires drawn by dry methods may be divided into several classes, depending upon the number of drafts taken. Single draft wires are given as light a coat as possible and drawn to the finished size in one draft at speeds ranging from a little over 100 to nearly 400 ft. per min., depending upon conditions. The reduction in size is usually on the order of $\frac{1}{32}$ in. in diameter and varies according to the purpose to which the wire is to be put. Only a lime coat is used if a bright finish is desired, the principal object of the drawing being to remove the inequalities of the finish and dimensions of the hot-rolled rod without hardening it too much. Such wire is used as stock for making bolts, rivets, screws, etc.

In another class fall the wires that are given two, three, or four drafts by dry drawing and practically all process wire for fine sizes. A large portion of finished wire is treated in this way. A sull coat is not absolutely necessary for only two drafts and may be omitted if a bright finish is desired, but both the sull coat and the lime coat are used when three or four drafts are to be taken. The lubricant used is of such a consistency that a second coat is not necessary at the dies after the first. In one procedure

used, it is customary to draw a No. 8¼ gauge wire from a No. 5 rod in the first draft and follow it with a draft to a No. 10½ wire in the second, a No. 12 on the third, and a No. 13½ on the fourth draft, corresponding to percentage reductions in successive drafts of 41, 35, 32, and 34 per cent. These values may vary in different mills according to the conditions but are fairly representative. Wires finished in these operations are used for hardware purposes, for galvanizing, and for many other applications.

In a third class belong those wires which are given two or three additional drafts beyond 13½ gauge to 16¼ or 17½ gauge, respectively, and those which are process annealed after four drafts from the rod to 13½ gauge, cleaned and coated, and then given four or five drafts to No. 20 gauge. The practical limit of drawing from the rod without annealing is about 17½ or 18 gauge in approximately seven drafts because the structure of the wire is badly distorted after this treatment and breakage usually results if further drawing is attempted.

The drawing of high carbon wires and alloy steel wires requires more care than is necessary for low carbon wires because of the greater hardness and poorer drawing properties of these materials. High carbon wire is used for wire rope, springs, suspension bridge cables, needles, and a large number of other specialized uses. Rods containing above about 0.30 per cent carbon are usually patented before drawing if more than one or two drafts are to be taken. The cleaning of high carbon rods and wire requires extra care to avoid a carbon deposit on the surface after pickling which has a detrimental effect on the surface finish. Heavier coatings must be used, a longer baking time is necessary in order to prevent brittleness due to absorbed hydrogen, and special lubricants of high quality are required. The speed of drawing, the amount of reduction per draft, and the number of drafts that can be taken without intermediate heat-treatment are all less than for low carbon steel.

The usual limit for dry drawing is between No. 17 and No. 20 gauge. For drawing wires to finer sizes than this as well as for all coarse wires that require special finish, wet-drawing methods are used. The principal differences between wet and dry drawing lie in the coatings applied and the fact that the wires are drawn wet. The coatings applied for wet drawing consist of either copper or tin or both. This very thin coating

is highly burnished by the drawing, thus producing a wire of high finish ranging in color from the reddish color of copper to the nearly white color of tin. These coatings are applied by dipping the carefully cleaned and rinsed wires in a vat containing a slightly acidified solution of copper sulfate and/or tin sulfate. The chemical reaction that takes place results in the deposition of metallic copper and/or tin on the surface of the wire accompanied by the dissolving of iron from the wire. The chemical reactions may be represented by the following:

$$CuSO_4 + Fe = Cu + FeSO_4$$
$$SnSO_4 + Fe = Sn + FeSO_4$$

Only a very thin coating is applied but it is quite soft and serves to reduce the friction between the wire and the die to a point where the drawing can be satisfactorily accomplished. From the coating tub the coil is immediately placed in a vat containing fermented liquor made from rye meal and yeast where it is kept until it is ready to be drawn. The liquor that adheres to the wire when it is withdrawn for drawing is sufficient lubrication for single draft drawing of the finer sizes. When drawing the coarser sizes, a concentrated soap solution is either dripped on the wet wire as it enters the die or the die is submerged in a tank of the soap solution. In continuous drawing of fine sizes, the blocks are mounted over a tank of soap solution, which lubricates the wires passing through it.

The procedure used in wet drawing is practically the same as for dry drawing. Since the wet process is more expensive than the dry, coarse wires requiring the wet finish are drawn dry to within one size of the desired gauge, cleaned, coated, and finished wet in one or two drafts. Wires of finer size than No. 20 gauge are drawn dry from the rod to about No. 13 gauge, the coil cut in two, and the bundles process-annealed or patented depending upon the composition. They are then cleaned, sull and lime coated, baked, and drawn dry to No. 20 gauge as described above, after which they are again cut in two. The bundles are again heat-treated to produce maximum ductility and are kept out of contact with oxidizing influences in this case. The bundles are then given a light pickle, coated with the desired metallic coating, stored in the fermented liquor, and then given the required number of wet drafts to reach the desired gauge. The

finest sizes usually require an additional heat-treatment at about 36 or 38 gauge.

Heat-treatment of Wire.—The following discussion will serve as a summary of the different types of heat-treatments to produce certain desirable conditions both in the wire during processing and in the finished sizes.

Annealing.—Process annealing is usually used for the purpose of restoring ductility and improving the drawing properties of hard-drawn, low carbon wire. Temperatures between 1000 and 1200°F. are usually used. The treatment may be carried out with or without protection of the wire from oxidizing influences, but some protection is nearly always used. Pot annealing of wire corresponds so closely to the box annealing of sheets that no more need be said about it. A method of annealing that is widely used is known as continuous lead annealing and consists in drawing the wire continuously through a bath of molten lead which is held in a shallow rectangular pan at the correct temperature. Sometimes two pans are used and the wire is preheated in the first pan and then brought to temperature in the second. Several strands are handled at once, drawn through the bath, and coiled on power reels located at the exit end. When the slight scaling produced by cooling in air must be avoided, the wires may be drawn through tubes that are sealed as tightly as possible. This continuous treatment has the advantages of close regulation of temperature and continuous operation, thus avoiding much handling of the material. Instead of the lead pans, furnaces equipped with refractory tubes through which the wire can be drawn out of contact with the hot gases are sometimes used. Its advantages are much the same as those for continuous lead annealing but it has the disadvantage in some cases of not being able to prevent scaling to a greater or less degree, depending upon the conditions of operation.

Dead soft or full annealing has as its usual purpose the entire removal of the effects of cold-drawing. Also, the grain size of the material may be adjusted by proper control of the time at temperature, the annealing temperature, and the rate of cooling. The temperature used is close to but above the upper critical temperature of the steel in question. This treatment is generally used when the finished wire is desired with no temper. It is sometimes used as the last annealing treatment and the hardness

subsequently raised to the desired amount by further cold-drawing. It can be carried out by either pot or continuous annealing methods. The ordinary tube furnace is not often used if the bright finish must be maintained unimpaired.

Bright annealing wire has the same purpose as discussed above. The difference in this procedure is that the wire, either coppered, liquor finished, or bright drawn, is heated in sealed pots under controlled atmosphere to prevent or minimize oxidation.

Patenting.—Patent annealing, previously discussed, is a controlled treatment used on rods above 0.40 per cent carbon prior to their drawing into wire. The purpose is to make the material tough enough to withstand severe distortion or drafting without actual or incipient breakage.

Normalizing.—Normalized rod and wire are used on grades of steel between 0.25 and 0.45 per cent carbon that is to be applied on cold upsetting or cold forging stock. The purpose is to produce a more plastic product from a high-strength material. Rod normalizing, as the term is used, differs from the usual meaning of the term as applied to other steel commodities. As practiced, the rods are heated to a temperature usually above the critical for a long period and then control cooled, to obtain softness and induce grain growth instead of grain refinement.

Spheroidizing.—The spheroidizing treatment, designed to produce maximum softness in any grade of steel, consists in heating for a long time at a temperature in the neighborhood of, but generally slightly below, the critical temperature range, followed by very slow cooling. This treatment is applied to the cold-drawn rods or on the final or finished wire. Spheroidized wire is used in the production of articles made by severe cold heading or cold forming.

Besides cold-drawing, the physical properties of high carbon wire may be adjusted over a wide range by hardening and tempering. The principles of these treatments will be fully covered in Vol. III of this series. Suffice to say here that hardening consists in heating the wire above its critical range and quenching it in water or oil, while tempering consists in heating to a low temperature for a short length of time and finally cooling to atmospheric temperature. The physical properties can be controlled by proper regulation of temperature, time, and the rate of cooling on quenching.

Finishing Operations.—Wire of the desired final size and finish is in the form of coils. If the wire is desired in straight lengths, one of several machines is used to straighten it and cut it into the desired lengths. These machines are entirely automatic in operation and work either on the principle of bending the wire in the reverse direction until it is straight or on the stretching principle.

Rigid inspection is a necessary final step in the preparation of steel wire. Preliminary inspection is made at several stages in the process but the finished wire is inspected for size, shape, finish, physical properties, surface, and internal defects. If the wire is not of the proper size, it may be due either to a worn die or to careless workmanship in drawing. Wire that is not of the correct shape is often due to the die's not being in proper alignment with the block, thus causing the wire to bear on one portion of the die more than on another. Physical tests taken on the finished wire include tests of tensile strength, temper (by bending), and electrical conductivity for certain uses of the wire.

The surface defects commonly encountered are scratches, slivers, and seams. Scratches may be the result of a poor die, improper lubrication, or careless handling. Slivers and seams are usually traceable to improper rolling of the rod or billet. Internal defects are caused by pipes, seams, and segregation and are very difficult to detect in the finished wire. X-ray methods of detecting them have been used in some cases. The drawing operation in itself is a severe test of the steel and most serious defects in the steel show up long before the wire is finished. Metal that will withstand severe cold-drawing is usually able to stand the stresses put upon it in service. This is not always true, however, and is no reason for relaxing the vigilance of the final inspection.

The application of protective coatings is the last step in the manufacture of wires that are to be subjected to corrosion in some form or other. The liquor finish on wet-drawn wires consisting, as it does, of a copper and/or tin coating is not heavy enough to be of much help in preventing corrosion of the steel beneath. The common coatings applied are zinc, tin, lacquer, paint, etc., but of these zinc is by far the most important protective coating and will be the only one considered.

The galvanizing process is a continuous one, several strands of wire being drawn at one time through the various steps in the process and coiled on separate power reels after galvanizing. As the process is usually carried out, the wires are process annealed in either tube furnaces or lead baths, cooled in air or water, and passed immediately into a cleaning tank of dilute hydrochloric acid where the scale is removed. The wires are next passed in succession through a rinse tank of hot water and a flux bath containing a dilute solution of zinc chloride. The wires are passed through a drier and then directly into the molten zinc. As the wires emerge from the galvanizing bath, mechanical wipers smooth out the coat. They are then cooled in air and coiled. The amount of the coat can be controlled at the wipers and by adjusting the temperature of the bath and the speed of travel. A quite recent continuous process cleans the wire by abrasives and anneals it in a tube furnace, the tubes of which contain a nonoxidizing atmosphere. The wires are then passed directly into the zinc kettle out of contact with air and without cooling. This process eliminates the cleaning and fluxing treatment and conserves the heat in the zinc bath.

Cold-forming Processes for Rods.—The specific methods of cold processing now employed are cold rolling, cold-drawing, cold-drawing and grinding, turning and polishing, and turning and grinding. Of these various methods, cold-drawing and turning and polishing are the most used, with the cold-drawing methods having distinct preference. This preference is due to the flexibility with which this method can be applied in the production of a wide range of shapes such as rounds, hexagons, squares, flats, and special sections, in addition to the physical properties produced and improved machinability.

Cold-finished material, regardless of the method of processing, is preferred over hot-rolled for any one of the following reasons: (1) special size accuracy, (2) smooth or bright finish, (3) characteristic physical properties, (4) better machinability.

Cold-drawn material is produced or drawn from hot-rolled bars or coils that have been especially prepared for the purpose. Cold-drawing, as the name implies, involves a stretching or elongation of the material. As the result of this action it is essential that high-quality hot-rolled material be used as such surface defects as scabs, slivers, seams, pits, and scale pits would

be accentuated. In addition, the steel must be free from chemical segregations, porosity, or pipe, or objectionable difficulties will be encountered such as size and section irregularities or breakage in the dies.

Cold-drawn material is produced from all the widely used plain carbon grades up to 0.50 per cent carbon. Most of the commercial grades used correspond to the following S.A.E. steels, although the cold-drawn grades are not usually specified in these terms: S.A.E. steels 1112, X-1112, 1020, X-1020, 1035, 1040, 1045, 1120, X-1314, X-1315, 1335, and X-1335. It should be noted, however, that practically any analysis of steel, plain carbon or alloy, can be cold-drawn if properly processed.

Prior to the cold-finishing operation the hot-rolled material is usually pickled in a dilute sulfuric acid bath to remove the rust and scale. The material is then rinsed and dipped into a lime bath which neutralizes any remaining acid and serves as a rust preventive and a lubricant in the finishing.

Cold Rolling.—Before the advent of cold-drawing methods, cold rolling was the only method for cold-finishing material. Today, however, very little cold-finished material is actually cold-rolled. This method now is confined to the production of specialties that do not lend themselves easily or economically to cold-drawing, such as wide thin flats, special sections, and small nut flats.

Cold finishing by cold rolling involves passing the pickled hot-rolled material repeatedly through a set of rolls, effecting a light reduction in each pass, until the desired size is obtained. Cold finishing in this manner produces a bright surface finish, size accuracy, and considerable increase in both the tensile strength and the yield point with the greatest increase in the yield point.

Cold-drawing.—In this method the pickled hot-rolled material of almost any shape is pulled through a die by means of a so-called draw bench mechanism. This mechanism is very similar to the bench used for the cold-drawing of seamless tube except that no mandrel is used. The material, if it is a bar, is first pointed and pushed through the die opening where it is gripped by the jaws of the draw head carriage. The carriage is then hooked to an endless block chain which furnishes the drawing power for the operation itself. The usual draft employed in cold-

drawing varies from $\frac{1}{32}$ to $\frac{1}{8}$ in. from hot-rolled to cold-drawn. The amount of draft employed varies with the bar size, section, chemical grade, physical characteristics, and finish required.

After cold-drawing it is almost always necessary to straighten the material to meet the exacting straightness required. For rounds, the most popular type of straightener is the Medart. This machine is a cross roll type consisting of one concave and one straight roll in which the bar is fed horizontally between the rolls which, when properly set, straighten the bar to fairly close accuracy. Small rounds approaching wire sizes are usually straightened by straight rolling through a series of horizontally arranged, staggered top and bottom rolls. Hand straightening, or power gagging, may also be used. Odd shapes, such as hexagons, squares, flats, and special shapes are straightened by the staggered roll type straightener or by gagging depending upon the section and the straightness requirements.

Cold finishing in this manner produces an effect similar to cold rolling, namely, bright surface finish, size accuracy, and increased tensile with particular improvement in yield point values.

Cold-drawing and Grinding.—In cases where the size accuracy, the surface finish, and the straightness produced by cold-drawing or turning and polishing are not satisfactory, the material is ground. The physical properties of the ground material will be unchanged.

Turning and Polishing.—In this operation the hot-rolled bar is subjected to a turning in which approximately $\frac{1}{16}$ to $\frac{3}{16}$ in. is turned from the diameter, depending upon the bar size, followed by polishing and straightening. By this method close size accuracy is obtained which approximates that obtained by cold-drawing, but the finish is somewhat brighter and surface decarburization, surface seams, and other hot-rolled defects that might cause objectional difficulties in cold-drawn material are removed. The physical properties will, of course, be those of the hot-rolled bar since no appreciable cold work has been effected.

Turning and Grinding.—This processing consists in turning the hot-rolled bar to remove the rough and imperfect surface followed by grinding, usually in a centerless grinding machine. The resultant product will have a finish and size accuracy similar to cold-drawn and ground material but will retain the hot-rolled physical properties.

Defects.—In cold processed material the inspection for defects involves those defects caused from steel difficulties and mechanical ones. The steel defects are the usual ones encountered such as seams, laps, cracks (probably the most prevalent), pipe, segregation (causes hard spots), slivers, and sliver pits. The mechanical inspection involves inspection for straightness, size, section, shearing, "die scratches," underfills (flat spots), overfills, etc.

Uses.—Cold-finished material has such widespread use that a complete list of the applications will not be attempted. A few of the more common ones are spark-plug shells, radio-speaker cores, bolts, nuts, screws, gears, pinions, parts for typewriters, sewing machines, and cash registers, motor and transmission shafts, piston pins, steering-gear arms, tie rods, gun parts, etc. Industries manufacturing automobiles, bicycles, typewriters, adding and calculating machines, textile machinery, shoe machinery, electric refrigerators, railroad equipment, agricultural equipment, and electrical equipment are particularly large consumers.

Suggested Questions for Study and Class Discussion

1. Give the disadvantages as well as the advantages of the continuous method of rolling the wire rod.
2. Describe the various preliminary steps that prepare the rod for dry drawing. Give the purpose of each step and the effects on the rod.
3. List and compare the various materials from which wiredrawing dies are made.
4. Compare wet and dry drawing from the standpoints of effect on the material and the cost of operation.
5. What are the advantages and disadvantages of continuous drawing?
6. What is patenting? When is it used and what are the effects on the material?
7. Compare cold rolling and cold-drawing of shafting as to cost of operation and effects on the steel.

CHAPTER XIV

GENERAL WELDING METHODS

In view of the fact that all but one of the various methods of making pipe and tube to be considered in Chap. XV are based on welding methods, it is believed that a short discussion of the general methods of welding steel is not out of place at this point. Welding, as a general method of fabrication, has not been looked upon with favor until recent years because the strength of the welded joint was almost entirely dependent upon the skill and care of the operator and consequently varied widely. With recent advances in the art of welding as well as much recently acquired knowledge concerning the metallurgy of the process, welding has reached a point of considerable prominence as a means of fastening pieces of steel together. Mechanical methods of welding pipe by pressure, however, have been in successful and quite satisfactory use for many years.

Welding may be briefly defined as a localized consolidation of metals by means of heat. It is usually employed to unite like metals for the purpose of transmitting considerable stress and the ideal weld is obtained when it has the same or better physical properties than the unaffected pieces joined by the weld. The processes known as *brazing* and *soldering* are used to unite metals when it is desired to transmit little or no stress and hence will not be considered here.

The welding processes may be roughly classified according to the condition of the metal surfaces in the locality of the weld during the operation of welding. On this basis, these processes may be classified as *plastic* and *fusion* processes, since the metal at and near to the welding surface is in either of these two conditions. The plastic zone extends from the melting point down to about 100°F. below this point. In the plastic processes, the application of external pressure is necessary to force the material together and effect the welding, but no added material (weld metal) is necessary. The parts to be welded

(base metal), being forced together, are reduced in length, width, or thickness as a result.

Fusion welding is a term applied to those welding processes in which the surfaces are in a fluid condition, although there are some indications that the metal is partly gasified in some electric arc processes. The surfaces being in a fluid condition, the addition of weld metal is necessary but no pressure is needed and the base metal parts are usually increased either in length, in width, or in thickness. A narrow space is provided between the surfaces for the weld metal. This separation aids in relieving internal strains on cooling and permits a more efficient weld than in plastic processes where the surfaces are forced into close contact. In either process the surfaces to be welded together must be free from foreign matter but the presence of mill scale is not particularly harmful if the welding operation is correctly carried out and is actually a help in some electric resistance methods.

The necessary heat in the plastic processes is produced by a furnace, by the electrical resistance of the base metal surfaces to the passage of current, or by a progressive chemical reaction (the *thermit* process) other than the chemical reactions involved in the combustion of fuel. The heat is produced for the fusion processes by the combustion of gases mixed in a gas torch, by an electric arc, or by the thermit chemical reaction. In some fusion processes a temperature of several thousand degrees Fahrenheit higher than the melting point of the steel occurs at localized points in the heating medium. The relations of the various methods of welding become apparent after consideration of the chart of Fig. 1-XIV, in which the names in bold face denote the common trade names of the processes. The characteristics of these methods overlap to a considerable extent in some cases and the chart, therefore, does not hold rigorously in all cases. The various methods indicated will now be considered briefly.

Forge Welding.—The term "forge welding" is applied to the plastic welding methods that utilize a forge furnace of some kind for heating the metal prior to welding. This is the oldest known method of welding and is the only one that has been in successful use for more than 40 years. The base metal parts are heated to a plastic condition in a furnace fired by coal, gas,

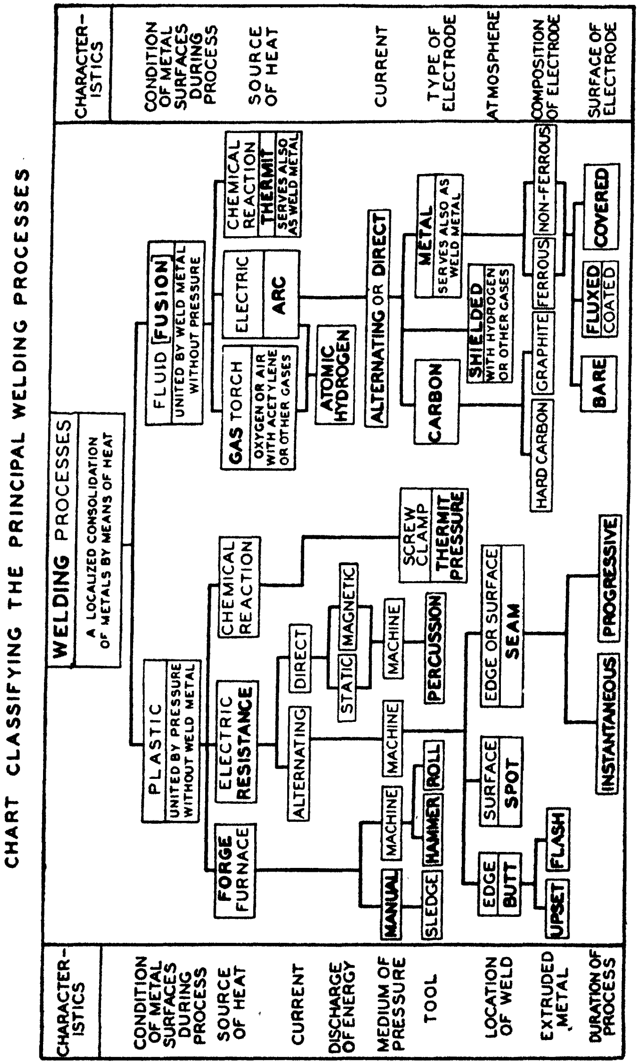


FIG. 1-XIV.—General welding methods. (*Courtesy of American Society for Metals.*)

or oil and then united by means of pressure. Two methods of applying the pressure are in general use. In one, the two base metal parts are placed together in the same plane with the surfaces to be welded together adjoining each other and the pressure applied by forces acting in the same plane as the pieces being welded—in other words, pushing them together. This method is known as *butt* welding. In the other method, called *lap* welding, the two pieces are placed in the same plane with their welding surfaces adjoining each other, but the edges are beveled (scarfed) in such a way that they overlap to a considerable extent and the pressure is applied by forces acting in compression in a direction perpendicular to the plane of the base metal. It is obvious that parts to be welded need not be in the same plane but they were considered to be in that position in order to make the foregoing description clearer.

In manual operation of forge welding the pressure is applied at high velocity in the form of blows from a light sledge, while in mechanical hammer welding, the blow is applied at lower velocity but the blow is heavier, either a drop hammer or a steam hammer being used. In mechanical roll welding, on the other hand, no sudden blow is used as the parts to be welded are forced longitudinally between rolls which transmit the necessary pressure. In all of these methods, the production of lap welds is more common. Butt welds may be produced by forcing the base metal through a die which is of such size and shape as to force the welding surfaces effectively together—in the butt welding of pipe, for example.

For forge welding, a material of rather low carbon content is required for successful operation, thus limiting its field of usefulness. Whereas only small objects can be welded by manual methods, quite large and heavy parts can be handled under the power hammer. By the use of forge welding, butt-welded pipe up to about 3 in. in diameter and lap-welded pipe up to about 30 in. in diameter are welded, the latter by rolls, while pipe up to about 8 ft. in diameter is produced by hammer welding.

Resistance Welding.—Electrical resistance welding methods depend upon a heavy, localized electric current and a great deal of mechanical pressure. An idea of the magnitude of these factors can be gained from the fact that for medium rolled steel the current and pressure required are about 30 kva. for 10 sec. and

between 5,000 and 8,000 p.s.i. of area to be united, respectively. With the exception of very small work, alternating current is used and, if different times of duration of current application are to be used, the power requirement varies in inverse proportion with the time. The mechanical pressure used is independent of the time but does have to be varied when different types of steel are being welded.

Three methods of resistance welding are in use, differing from each other in the method of current and pressure application. The three are known as *butt* welding, *spot* welding, and *electropercussive* welding. Variations of each are in use. For example, *upset* and *flash* welding are forms of butt welding, *projection* welding is a variation of spot welding, and *seam* welding involves methods allied to both butt and spot welding. In these resistance-welding methods, the correct properties of the electrode die are all important to the success of the process. These dies require the best thermal and electrical conductivity that it is possible to combine with great hardness and sufficient strength to exert the pressure. The best combination of these properties is obtained by using a hard copper electrode faced with one of several alloys whose hardness at the working temperatures is much greater than that of copper.

In *butt* welding, two pieces of the same cross-sectional area are gripped by the electrode dies and pressed together while the necessary heat is generated by passing a very large electric current through the area of contact. The gripping dies conduct the current to and from the work. The greatest portion of the resistance, and, therefore, the heat, occurs at the joint where it is needed most. The *upset* form of butt welding consists in maintaining a high and uniform compression during the operation, the temperature at the joint being kept below the melting point of the steel. This method forces some of the base metal upward in a rough convex shape which is usually ground off as a finishing operation. By placing a die of appropriate shape around the joint, this extruded metal can be made to take a desired size and shape, thus producing a kind of forging.

The *flash* welding variation of the butt resistance weld process is much like the upset method in a mechanical way but, after the pieces are brought into contact and heated, the pieces are separated slightly. This separation produces an intense sparking

effect at the welding surfaces and raises the temperature very rapidly. The actual welding is then carried out under high pressure and at a temperature at the joint sufficient to melt a small portion of the metal. The melted portion is extruded out by the pressure in the form of a fin which is subsequently ground off. This method is in wide use on large work because it is rapid and does not require such high pressures as the upset method, but for smaller work a combination of upset and flash welding is generally used. The parts are not separated but the flashing effect is produced by automatic and successive changes in current and pressure. It is obvious that the tighter the welding faces are forced together, the less will be the electrical resistance that the joint offers to the passage of the current. In some cases a moderate pressure and current are used to bring the joint almost to the fusion point and, when conditions are just right, a heavy current and high pressure are suddenly applied to complete the job. As there is no hesitation in the cycle to allow for flashing, this form of flash welding is very rapid in operation.

In *spot* welding, two or more sheets of base metal are held between pointed metallic electrode dies and a heavy current at comparatively low voltage is passed from electrode to electrode through the base metal. When the portion of the sheets between the dies reaches a plastic welding temperature, the electrodes are rather suddenly forced together by a pressure sufficient to unite the sheets at a spot of about the same size as the points of the dies. The current is then shut off and the pressure maintained for a short time thereafter. The so-called *projection* welding method is a variation of spot welding in which small ridges or other projections are formed on the welding surfaces before welding by rolling or forging. The purpose of the projections is to localize the current and thereby produce more intense heat at these points. In *seam* welding two or more bars or sheets are passed between electrode rollers or a succession of dies which transmit the current and mechanical pressure necessary to produce the welded joint. A long weld may be produced in this manner in a comparatively short time.

The *electropercussive* welding method is different from other resistance methods in several respects. Direct current is used entirely and the surfaces are finally raised to a temperature

at which they are partly fluid by a sudden discharge of electrical energy in the form of an arc between the pieces. This arc is extinguished by a sudden compressive blow which forces the base metal pieces together and completes the weld. The electrical discharge is either electrostatic or electromagnetic in character.

In any of the resistance-welding methods certain precautions are necessary in order to produce a satisfactory weld. If the electric power used is too high or the duration too long, the metal will be burned and the weld will be of inferior strength; if too low, the weld cannot be made. Too high a mechanical pressure distorts the shape of the weld beyond the desired amount, while too small a pressure will fail to unite the base metal pieces satisfactorily. With a properly designed and operated machine, however, welds can be produced by all the above-mentioned methods which are equal in physical properties to those of the base metal parts.

Except for small parts, the machinery necessary for resistance welding is so large that it cannot be made portable. The foregoing methods are, therefore, essentially factory operations and are very widely used in production work. About 75 per cent of all welding is accomplished by resistance methods when based on the value of the product. The methods of butt resistance welding are applicable to both thick and thin sections and are used when a strong joint is required. By a combination of flash and upset methods, cross sections of over 50 sq. in. have been welded successfully. Flash welding methods are extensively used in assembling automobile bodies and in joining lengths of tube and pipe. Flash welding has the advantage of being applicable to welding pieces whose edges are not exactly true. The upper limit of thickness that can be handled by spot welding methods is under ½ in. owing to the excessive currents and mechanical pressures required for heavier sections. At these greater thicknesses, trouble is also experienced because the heat is conducted away from the spot by the base metal pieces too rapidly for the material between the electrodes to be raised to the necessary welding temperature. Various methods of localizing the spot still further, such as buttons on one of the pieces, have not proved commercially feasible. Seam welding is subject to the same limitations as spot welding. Percussive methods are particularly suited to the multiple

welding of different metals or different types of steel as in the manufacture of some tools where it is desired to join a costly head to a cheaper supporting base.

Thermit Pressure Welding.—The chemical reaction known as the *thermit* reaction consists in igniting a mixture of metallic oxide and finely powdered aluminum. The reaction is exothermic in character and evolves such a tremendous amount of heat that the reaction, once started, proceeds of its own accord to completion, producing a highly superheated metal and a slag of molten and highly fluid aluminum oxide. Fe_3O_4 is used in the case of steel welding, and it has been found that a certain size of oxide flakes, a certain percentage of fines, and a proper balance between the oxide and the aluminum are necessary before the welding can be done satisfactorily. If the mixture is not properly adjusted, considerable trouble will be experienced. The chemical reaction for thermit welding of steel may be represented by the equation

$$3Fe_3O_4 + 8Al = 9Fe + 4Al_2O_3$$

This reaction is used both in fusion and plastic welding methods, both of which will be described.

The thermit pressure welding process is also known as the thermit pipe welding process because at one time its most prominent use was in connecting the ends of pipe, although it has a much wider field of application at present. The products of the thermit reaction are used merely to bring the surfaces to be welded to the proper temperature. In welding pipe, the ends are cut square and faced, the threaded portions removed, and the pipes butted together by means of clamps and longitudinal bolts. Light cast-iron mold segments are placed around the pipe, thus forming a channel around the point into which the highly superheated products of the thermit reaction are poured. The thermit mixture is ignited in a crucible and the reaction allowed to go to completion before pouring the contents into the annular channel. The alumina, Al_2O_3, enters the mold first and coats it and the pipe, protecting both of them, in this way, from the superheated iron. In a short time, varying from a few seconds to several minutes, the joint is raised to the plastic stage and the necessary pressure is applied by turning the bolts. The clamps and mold are usually removed immediately, allowing

the reaction products to flow away so that the mold can be used again. A slight enlargement on the outside of the pipe results from this method of welding.

Thermit Fusion Welding.—Turning to the fusion processes for welding, the *thermit* process will be described first because of its relation to the plastic process in which the thermit is also used. The fusion process differs from the foregoing in that no pressure is applied and that the superheated iron produced by the reaction is allowed to flow into the joint and form the weld by bonding with the base metal parts. In case alloy steels are being welded, additions of alloying elements to the thermit mixture can be made in order that the weld may have practically the same composition as the base metal parts.

In the operation of the process, the parts to be united are separated by a space, the size of which depends upon the size of the base metal parts. The surfaces are thoroughly cleaned by sandblasting and then trued up parallel to each other by means of a cutting torch. The small amount of scale formed in this step appears to be beneficial to the welding operation. A wax pattern is then placed around the parts, the pattern being of the size and shape of the reinforcement desired. If two solid pieces are to be welded together, the space between them is merely filled in with the wax. A sheet-iron box is then placed around the pattern and, after the wax has hardened, the ample space provided between the box and pattern is rammed up with sand. Pouring and heating gates, as well as risers, are provided in this improvised mold. A flame is then directed through the heating gates, melting the wax and baking the mold. The removal of the wax leaves the space vacant into which the thermit mixture can flow. The heating is continued until the faces to be welded are at a red heat. A proper amount of the correct thermit mixture is placed in a crucible supported over the pouring gate and ignited. The reaction is completed in less than a minute and the thermit steel is tapped from the bottom of the crucible into the pouring gate. The highly superheated metal flows around and between the parts to be united and thoroughly fuses with their surfaces, thus welding them into a homogeneous mass. The molten slag overflows into a basin at the top of the mold and protects the steel from oxidation during pouring and solidification.

The thermit fusion process can be seen to be really a method of casting superheated metal of the same composition as the base metal into a mold for the purpose of bonding at least two parts of the mold together (the base metal parts). The same precautions that are necessary in foundry work apply here. The process is used where great strength, ductility, and soundness are required in the repair of large objects. It is sometimes used as a means of putting large steel objects together, as well. The method can be used wherever space is at hand for placing the mold. An ordinary thermit weld, as cast, will have a tensile strength of about 70,000 p.s.i. and a normal amount of ductility. These properties can be varied by adjusting the composition of the mixture.

Gas Welding.—In Europe the term *autogenous* is applied to any method of fusion welding by means of gas or the electric arc. The same term is applied in this country to some extent but the processes are more usually separated, and called gas and arc welding, respectively. In gas welding, the heat is supplied by a flame resulting from the combustion of acetylene, hydrogen, or other combustible gases under pressure in an atmosphere of compressed oxygen or air. The two gases are mixed in a torch that can be regulated to produce a flame of certain desired properties. The torch is so constructed that the gases are supplied to the mixing chamber through separate passages, and their pressures can be independently adjusted at the torch. The torch tips, through which the gases are ejected for burning, are of different sizes for various kinds of work but are constructed in such a way that the gases burn at the orifice in the form of an incandescent cone. In acetylene welding, the amounts of oxygen and acetylene should be regulated to give a neutral flame because if excess acetylene is used, the flame is carburizing in nature (adds carbon to the steel being welded) and if excess oxygen is used, the flame is, of course, oxidizing in character.

The gas welding process is best suited for making butt welds, although other types can be made satisfactorily by it. The faces of the two base metal pieces are beveled prior to welding so that the weld metal may be deposited in the V-shaped opening formed when the pieces are assembled. The pieces are rarely butted tightly together at the base of the V, but a narrow open space is usually left as the depth of the V is not quite so great as

the thickness of the base metal pieces. In some cases, both edges of each piece are beveled so that the opening left when the pieces are placed in position takes the form of a double V with the bottoms of the two V's together. In this way, one-half of the weld metal is deposited in one V, the piece turned over, and the other half of the weld made. The weld metal is usually supplied independently in the form of single pieces of welding rod whose size, composition, and flux coating, if any, vary with the size and character of the work to be done. In some cases, particularly in thin material and in the repairing of cracks in castings, the weld metal may be taken from the base metal.

In manual welding the operator holds the torch in one hand in such a position that the tip of the cone of the flame just fails to touch the base metal, while with the other hand he keeps the end of the welding rod close to the work. He moves the flame back and forth over the base metal, first slightly ahead of the portion actually being welded to preheat it and then at the weld in order to melt that portion into a puddle. The rod is melted by heat radiated from the molten puddle and the flame, the melting of the rod adding to the volume of the puddle in order to fill up the V-shaped cavity. When the molten metal deposited in the puddle gets large enough, the flame and rod are moved on and the deposit is allowed to solidify and cool gradually as a homogeneous mass. In this way, the line of the joint is preheated gradually to the melting point, the weld metal deposited, and the weld allowed to cool slowly. If a single V-shaped cavity is used, the piece is turned over if possible and the bottom of the V reinforced with weld metal, producing a slight protrusion. In any event, excess weld metal is added in the V, thus giving a convex shape to the top of the weld.

In many welding jobs, the base metal must be preheated before welding is started. This can be done with the torch, but by using cheaper gases than acetylene and oxygen, or in a furnace. Preheating minimizes the tendency of cooling strains in the metal as the heat generated in welding is conducted back for quite a distance in the base metal, which must not be heated or cooled rapidly if it possesses low ductility. Preheating also saves money in the form of the expensive gases. In addition, heating in a furnace will save time.

Automatic gas welding machines are being used in increasing numbers at the present time because they reduce the effect of the personal equation in regard to the strength of the weld. The only thing that the operator has to control is the maintenance of a neutral flame. For field work, of course, the manual method is used. The convenience and ease with which gas welding can be done make it a popular method of welding for many purposes. It is widely used in welding pressure drums in all sizes, for welding pipes and fittings, and in the repairing of heavy steel parts and castings of all descriptions.

Arc Welding.—In all the many methods of arc welding, an electric arc is struck between an electrode and the parts to be welded. In this way, intense heat is generated which fuses the parts to be welded. Direct current is used in most arc welding, but alternating current is used where the lighter weight of the alternating transformer equipment is advantageous, such as in building frame construction. A greater amount of heat is generated at the positive pole of the d.c. arc and for this reason the base metal forms the positive pole and the electrode the negative when large pieces are being welded. In welding thin material, high carbon steels, or some alloy steels, the polarity is usually reversed, the electrode being the positive pole. As in gas welding, the operation of arc welding can be conducted manually or by automatic machines. In the latter case, only the feed of the electrode may be automatically controlled or both the feed and travel controlled.

Both the metal arc and the carbon arc processes are in use but the former is more prevalent at the present time. In the metal arc process, the electrode is made of metal of approximately the same composition as the base metal parts. It acts as one pole of the circuit and provides weld metal to the weld by the melting of its end which, of course, is in the intense heat of the arc. When the welding is done manually, the electrode is handled by means of a holder so that only one hand is required. In the *carbon arc* process the electrode is composed of carbon and is used only to strike and maintain the arc. The weld metal is either taken from surplus base metal or supplied by a welding rod which is manipulated in much the same manner as in gas welding.

The weld metal is furnished in the form of a wire, commonly called a *welding rod.* In manual operation, the common sizes of wire used are $\frac{5}{32}$ and $\frac{3}{16}$ in. in diameter and these sizes require in the neighborhood of 160 and 200 amp. of current, respectively, at about 20 volts. In automatic welding, the machines use larger sizes of rods and more current. With either type of operation, the wires may be bare or may be coated with either a slagging or a fluxing medium. These materials melt at about the same rate as the metal core and serve to protect the molten puddle from oxidation. Such a *fluxed* rod permits the use of larger sizes of rod, higher currents, and greater speeds as well as ensuring at least some increase in the ductility of the weld. Fluxed rods are very necessary if alternating current is used. Some rods, known as *covered* rods, either have an outer covering of fabric that retains a flux that will not stick to the rod of its own accord or the fabric itself is impregnated with a fluxing material.

Arc welds having a depth of not over $\frac{3}{8}$ in. are usually made in one layer; if $\frac{1}{2}$ in. in thickness, two layers are made, one on top of the other; and, if the weld is over $\frac{3}{4}$ in., three or more layers are laid down. If possible, it is well to peen the inner layers with a hammer after laying them down as this strengthens the weld. The process will make welds in any position—horizontal, vertical, or overhead—and is adapted to lap, butt, and fillet types of welds.

Several special arc-welding processes in use merit brief description. Most of these were developed to permit the use of larger electrodes, higher currents, and greater operating speeds than are possible by ordinary operation with bare welding rods. Automatic machines are used, for the most part, together with coated welding rods of one type or other. Furthermore, it is claimed that these special processes produce a weld with greater ductility than that obtained by ordinary methods.

In the *shielded arc* process, both the electrode and the deposited metal are shielded from oxidation by the maintenance of an atmosphere of hydrogen, water gas, alcohol vapor, or some such reducing medium around the arc. In another allied method, a bare metal electrode moves with an oscillating motion through a thick mass of fluxing material which serves as a shield for the arc and permits the deposited material to cool slowly, thus pro-

moting ductility in the finished weld. In the *electronic tornado* process, an arc shielded by some nonoxidizing vapor is used. In addition, the arc is maintained in a strong magnetic field. This process utilizes a carbon electrode.

Atomic hydrogen welding has received much publicity in the past few years. This method is partly a gas and partly an arc process. A fine jet of hydrogen gas is forced through an a.c. arc formed between two tungsten electrodes. The high temperature existing in the arc breaks down the molecules of the hydrogen gas into atoms which recombine into molecules after leaving the arc. In recombining into molecules, the gas gives up or evolves the heat stored in it by its dissociation in the arc, producing a flame of hydrogen which is hotter than any other known flame. It can be seen that while an arc is the initial source of heat, the base metal forms no part of the electric circuit but is fused by heat from the hydrogen flame as in gas welding. The weld metal is usually supplied independently as in ordinary gas welding but surplus base metal is sometimes used instead, if available. The process is largely used on thin materials at present as the magnitude of the current and hence the temperature attained by the arc are limited by the combustibility of the tungsten electrodes. The method can be used to great advantage in welding high nickel and high chromium steels but will produce a sound, smooth weld when used on many other types of steel.

The strength of the welds made by the electric arc methods depends upon the grade of weld metal used and the care and judgment exercised in the operation of the process. By using welding rods of alloy steels quite high physical properties can be attained. The heat-treatment of unalloyed welds does not produce enough betterment in properties to warrant its use in most cases, but an increase in ductility can be obtained by annealing alloy welds. Cooling strains can be relieved by annealing in any case, however, and this produces beneficial results to the piece in general in many instances.

The metal arc process is an excellent production tool and is extensively used in welding the longitudinal seams in large pipes, in the fabrication of pressure vessels, and in the construction of machinery bases and other heavy parts. Its field of use is being rapidly extended to the structural steel business to replace rivet-

ing and in marine construction. This has been mainly due to its simplicity of operation, the saving of weight in design made possible by its use, and its ready adaptation to all kinds of reinforcement.

Gas Cutting.—Although the process of cutting ferrous materials by means of a torch is not a welding process, it is included

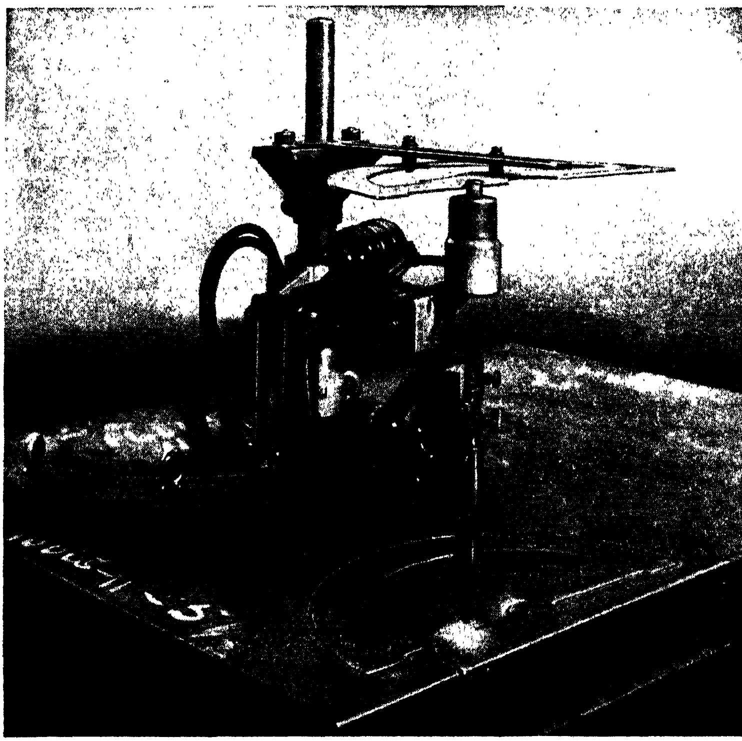


FIG. 2-XIV.—Automatic machine for gas cutting. (*Courtesy of the Air Reduction Sales Company, Inc.*)

in this chapter because it is performed with the aid of a torch whose construction, fuel, and operation are very similar to those employed by gas welding.

The use of a cutting torch in the fabrication of ferrous materials is of comparatively recent origin but is coming into popular usage at present. A modified form of the acetylene welding torch is used, although hydrogen and natural and artificial

gases can be burned in it instead of acetylene. The cutting torch is provided with an additional third passage for the transmission of oxygen under high pressure. The oxyacetylene flame does not do the cutting but merely heats the spot to be cut to a red heat while the high-pressure oxygen jet performs the cutting action. At the red heat, the oxygen in the jet rapidly combines with the metal, forming iron oxide, which is immediately blown out of the hole by the high-pressure oxygen. A small hole can

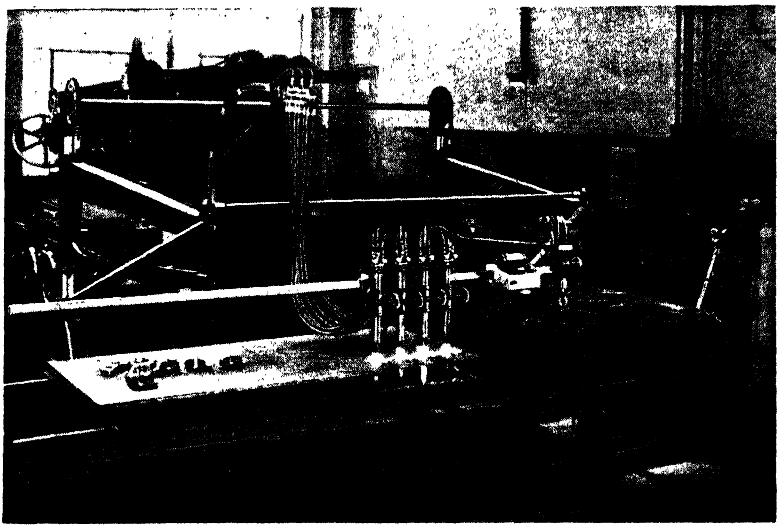


FIG. 3-XIV.—Multiple automatic machine for gas cutting. (*Courtesy of the Air Reduction Sales Company, Inc.*)

be very rapidly made through a thick piece of steel by this method. If the torch is moved along the piece, a slit can be very rapidly formed which extends through the metal. Except for about ⅛ in. on either side of the cut the metal is entirely unaffected and a clean smooth cut can be produced which is but very little wider than a saw cut. The method can be used either manually or with automatic machines. Plain carbon steels up to about 0.30 per cent carbon can be cut cold, but high carbon and alloy steels must be preheated and annealed after cutting to prevent cracking.

Gas cutting by automatic machines is being used as a method of fabricating parts from rolled steel plate which formerly could

be made only by casting. The part can be accurately cut to size, the cut has a better finish than can be obtained by sawing, and the operation is much more rapid. In addition, the parts have the usual inherent advantages of rolled material over castings. Figure 2-XIV shows an automatic machine that can be mounted directly on the plate being cut. A steel template, shown at the top, is provided of the exact size and shape of the desired part. The small electric motor drives a magnetized roller around the template, the torch accurately following the path which the roller traces on the pattern while cutting the part from the plate. The magnetic attraction between the roller and the template holds the roller firmly to the template and ensures the accuracy of the part. The part shown in the figure was cut in 30 min. from a plate 5½ in. thick. Figure 3-XIV shows in operation a multiple automatic machine which is capable of cutting four pieces at once. The principle of operation is the same as for the portable machine.

Suggested Questions for Study and Class Discussion

1. Define welding. Classify the welding processes.

2. Compare forge butt welding and resistance butt welding as to method of application.

3. What differences in method of application exist between thermit pressure welding and thermit fusion welding?

4. Explain how it is possible to cut steel with an acetylene torch.

5. Give three practical applications of each of the general welding methods.

CHAPTER XV

THE MANUFACTURE OF TUBULAR PRODUCTS

Tubular steel products are those cylindrical forms variously termed pipe, tubes, tubing, and casing which are used for conveying gases, liquids, solids and for a large number of mechanical and structural purposes.

In the subsequent discussion certain terms will be used in describing sizes and other characteristics of these particular products which in many cases are difficult to define absolutely. This is particularly true when an attempt is made to distinguish between the use of the general terms pipe, tubes, and tubing. It is found that the descriptive terms have grown with the industry and are best defined according to the usage.

Size.—The common designation for tubular products is in terms of either the inside diameter (I.D.) or outside diameter (O.D.). Other terms in addition to diameters, such as wall thicknesses, foot-weights, and the terms "actual" and "nominal," are used in referring to sizes. Nominal used in the discussion refers to the given dimensions as distinguished from the actual or real dimensions. If the reader will refer to a table listing pipe sizes, he will immediately see that there is considerable difference between the actual and the nominal dimensions. For example, 1-in. standard weight pipe has an O.D. of 1.315 in. and an I.D. of 1.049 in.

The nominal dimensions of pipe (diameter, wall thickness, and weight) have been standardized and adopted by various associations for general use by the manufacturer and consumer. The accepted standards for standard weight pipe are the outgrowth of the formulation of Robert Briggs, which has been extended beyond Briggs's originals to include pipe 12 in. in size. Specifications for standard pipe may be found by referring to manufacturers' handbooks or the standards as published by the various societies.

Many tubular products have different weights or wall thicknesses for a particular size. In these products the outside diam-

eter for the size remains the same with the inside diameter being changed according to the specification. Such products as pipe 14 in. or larger (large O.D. pipe), American Petroleum Institute casing, drill pipe, plain end pipe, pressure tubes, and mechanical tubing are described according to their actual outside diameters and foot-weights or wall thicknesses.

The weights of tubular products are calculated on the basis of 0.2833 lb. per cu. in. and are expressed as weights per foot, or foot-weights. The foot-weight of pipe with threads and couplings is based on the weight of a 20-ft. length including one coupling.

Tubular products are furnished in varying lengths as (1) in single or double random lengths as produced on the mill, (2) in average lengths, falling between specified limits, (3) in definite cut lengths, or (4) in welded double lengths.

Processes.—The welding processes for making tubular products comprise the welding process, the seamless process, and shop fabrication. The welding process involves several methods for the manufacture of tubular products from flat-rolled materials known as skelp, plates, and strip. These methods are butt welding, lap welding, forge or hammer welding, fusion welding (electric-arc, or gas or combination with no mechanical pressure to effect the welding), and electric resistance welding. The seamless process comprises two general methods known as hot piercing and cupping. Shop fabricating involves the processing of lock bar pipe and riveted pipe.

Steel.—The steels used for the manufacture of tubular products are made by either the acid Bessemer, open-hearth, or electric furnace process. In general, acid Bessemer or open-hearth steel is used for the welded products, open-hearth or electric furnace for seamless, and open-hearth for fabricated pipe.

Tubular products are, in general, made for a specific application. Thus, if the intended use of the material and the physical properties needed to fit the use are known, the manufacturer is in a position to use the type and composition of steel and method of manufacture needed to produce a satisfactory product. For these reasons, chemical specifications commonly impose limitations on phosphorus and sulfur only, except in the case of alloy steels, where limits for the alloy content are also included.

Coatings and Linings.—"Black pipe" is the common name given to uncoated pipe and to pipe that has been given an ordinary air-drying lacquer coating for protection against rust during shipping. This latter process is a regular mill practice.

For various specific applications, pipe is furnished coated or lined, or both, with a variety of metallic or nonmetallic materials. The metallic coating commonly applied for protection against corrosion is zinc, which is applied either by electrolytic methods or by the hot-dip process.

FIG. 1-XV.—A continuous skelp mill in operation. (*Courtesy of Jones & Laughlin Steel Corporation.*)

A large tonnage of pipe for line uses is coated or lined, or both, with tar base or asphalt base materials, by brushing, hot dipping, spraying, or centrifugal spinning. Pipe is also furnished internally lined with cement to meet such conditions of corrosion that will be withstood by the cement.

Pipe is also furnished in the pickled condition. After the pickling to remove scale and dirt, it is common practice to apply an oil coating.

Rolling the Skelp.—Skelp is, in reality, merely a special form of strip which is particularly adapted to forming into pipe. It is made in such widths and thicknesses that when the skelp is bent longitudinally into the desired shape, a pipe of the required outside diameter, inside diameter, and wall thickness will result. Skelp is usually rolled on a continuous mill much after the manner of strip. Twelve to fourteen horizontal stands are provided

together with one or more edging stands, usually located in the intermediate set. Continuous furnaces are provided for furnishing the mill with hot blooms or billets. In the roughing set of four or five stands the metal is reduced in section by tongue-and-groove passes. The first and third passes are often provided with knobbed rolls which knead the surface layers of the metal by means of knobs or projections upon them. This kneading action,

FIG. 2-XV.—The skelp clipper in operation. (*Courtesy of Jones & Laughlin Steel Corporation.*)

called *Spellerizing,* seems to increase the resistance of the finished pipe to corrosion by pitting. The second and fourth stands remove the effects of the kneading action. In the intermediate set, the piece is further reduced by tongue-and-groove passes while edging stands roll the edges, giving them a slight bevel so that the edges will fit together squarely when the skelp is formed into a butt-welded pipe. For lap-welded pipe, the skelp is sometimes scarfed in the finishing stands so that when shaped, the edges will overlap to the desired amount. The finishing set is otherwise composed of plain rolls and accomplishes the last bit of reduction to the desired size. The mill is usually split into

groups of stands in tandem so that the piece will run free between them. The finished skelp is run along the delivery table to the shear, where it is cut into sections somewhat longer than the desired lengths of the finished pipes and then piled on the cooling bed by an automatic piler. The standard lengths of finished pipe are 20 and 40 ft. The cooled and inspected skelp is then conveyed to the pipe and tube mills for conversion into tubular products.

Skelp is heir to most of the defects that occur in strip rolling and need not be discussed here. The width, thickness, and

FIG. 3-XV.—Charging the butt-weld furnace. (*Courtesy of Jones & Laughlin Steel Corporation.*)

shape of the edges of the skelp should be carefully watched if the desired results are to be obtained in the pipe mills.

Butt-welding Process.—Butt-welded pipe is made in all sizes from ⅛ to 3 in. in diameter. The procedure consists in shearing one end of the length of skelp to a tapered tongue, heating it to a good welding temperature, and drawing it through a bell-shaped die which forms it into a circular shape and welds it in one operation. The pipe is then run through a sizing machine, scale-removing rolls, and a straightening machine in succession, after which it is cut to size, the ends threaded, and the finished pipe inspected and tested.

From the cooling bed the skelp passes to the clipper, a machine that acts both as a shear and as a press. One end of the skelp

(sometimes two strips at a time) is placed in the machine which shears two triangular shaped pieces, one from each corner, and cups the pointed end to start the curve for welding. This tongue-shaped end is then bent upward just back of the cupped portion so that when the skelp lies flat on the furnace hearth this end will stick up enough for the welding tongs to grasp it easily. The clipping and cupping must be symmetrical or the skelp will stick in the die. The machine is usually placed beside the welding furnace on the charging side.

The welding furnace is usually gas or oil fired and is rectangular in shape with a low roof. It is made about 2 ft. longer than the skelp being charged and wide enough to accommodate quite a number of strips lying side by side. Only a narrow horizontal slit running the width of the furnace is provided at each end for charging and discharging the skelp. The bottom of the furnace is made up of high-grade silica sand covered with a layer of broken chinaware. This is necessary as it has been found to stick to the skelp less than any other bottom material. An electric charging machine travels back and forth on rails laid across the charging end of the furnace and is able to charge the skelp very rapidly. The furnace is made of such a width that by the time the charging machine has covered the furnace bottom with skelp, the first strip charged has reached the welding temperature.

The welding temperature of steel pipe usually runs within the following ranges:

Bessemer steel	2375–2450°F.
Open-hearth steel	2425–2500°F.

The furnace temperature in the butt-welding operation is slightly higher, ranging from 2550 to 2600°F.

The welding machine is located opposite the delivery end of the furnace. It consists of a long, narrow carriage with an endless, sprocket-driven chain mounted on it. The front end of the carriage is free to move on a track back and forth in front of the furnace while the rear is usually pivoted. The front end also carries a stop for the welding bell and a platform on which the welder stands. The welding die, called a welding *bell* because of its form (Fig. 4-XV), is made of a special grade of cast iron and is so shaped inside that as the skelp is pulled through it,

the strip is gradually bent into the form of a pipe and its edges forced together, thus forming the weld.

In the welding operation, the welder grasps the pointed end of the skelp in the furnace with a specially designed pair of tongs. He then slips the welding bell, larger end first, over the handles of the tongs and drops the ends of the tongs between the prongs of the bell stop in such a way that a knob on the tong handles engages with the draw chain. The chain in traveling away from the furnace draws the tongs and skelp out of the furnace. When the bell reaches its stop, the chain draws the tongs and skelp through the bell, forming the skelp into a pipe. The tongs should

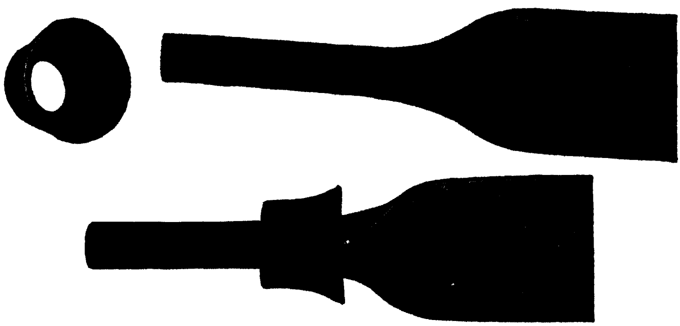


FIG. 4-XV.—The welding bell in operation, showing the manner in which it bends the skelp. (*Courtesy of Jones & Laughlin Steel Corporation.*)

necessarily be so designed that no section is larger than the inside diameter of the bell and should have a locking device so that they will not let go at any time during the above procedure. The operation of the process is very rapid, as over 250 lengths of 1-in. pipe, each 20 ft. long, can be welded per hour. For very small pipe, tongs small enough to go through the bell cannot be easily made and a steel bar is welded to the pointed end of the skelp prior to charging. The same is true of very thick walled material because small tongs cannot be made strong enough. So-called "double extra strong" pipe is drawn through several bells of decreasing size in order to form and weld it. It must be reheated before each pass.

The welded pipe is released from the tongs and immediately pushed down an inclined skid to a trough that contains live rollers and propels the pipe to the sizing rolls. These are electrically driven cast-iron rolls of large diameter and small width as

they contain only a single pass of a size very slightly larger than the outside diameter of the finished pipe. One-half of the circular section is cut in each of the two rolls. The welding bell and skelp are purposely made oversize to allow for the finishing operations. The sizing rolls compress and elongate the pipe and form it into an exactly circular section. The weld is also improved somewhat in the process.

The sized pipe is delivered to a trough with an automatic kickoff and delivers the pipes to a cooling rack on which their direction of travel is at right angles to that of their passage through the sizing rolls. This rack is a steel framework inclined upward slightly toward the delivery end and the pipes are rolled up the incline by fingers on motor-driven chains. The rolling of the pipe keeps it straight and round during its cooling period. The purpose of this cooling rack is to reduce the temperature of the material to a point just above the critical range before delivering it to the scale-breaking rolls. At the temperature of the sizing operation, both the scale and the steel are soft and consequently not very much of the scale is removed. Just above the critical temperature, however, the scale is brittle and can be cracked off easily while the metal is still comparatively soft and ductile. The cooling table delivers the pipes at the desired temperature directly to trough rollers which convey them to the scale-breaking rolls.

The scale-breaking machine usually consists of three two-high stands of rolls, the center stand being vertical. All are placed fairly close together. The first two stands elongate and compress the pipe very slightly while the last stand sets the exact final diameter. Circular grooves of appropriate size are cut in the rolls to accomplish this purpose. The slight compression cracks off the very brittle and hard welding scale on the inside of the pipe as well as the scale formed on the outside of the pipe after welding. As the pipe is now below a heavy scale-forming temperature, only a darkening of the surface results after the pipe is delivered from these rolls. The scale is blown from both the inside and outside of the pipe by compressed air when finished.

The pipe is immediately transferred across another cooling rack to a set of straightening rolls. In this straightening machine, two electrically driven rolls each about 4 ft. long and from 10 to 20 in. in diameter are set with their axes askew but with

their center points lying opposite each other. They are set side by side and inclined to each other at an angle of about 30 deg. The roll bodies are machined to a concave shape so that a pipe lying between them is in contact with them through their entire length. In operation, the rolls are revolved rapidly and a pipe is fed endwise into the space between them. The pipe is grasped by the rolls, revolved rapidly, and pulled slowly through them. The pipe emerges practically straight and with a smooth surface, and is delivered upon a cooling rack where it cools to room temperature.

The finishing operations include cutting, threading, inspecting, testing, and coating. In some plants, circular cold saws are located on each side of the final cooling table and are adjusted at the correct distance apart to cut the pipe to the desired lengths. The saws are stationary and the chain-driven fingers on the cooling table move each pipe in succession to the saws. The cooled pipes collect at the end of the table, are blown with air to remove any loose scale, and are taken in bundles by a crane to automatic threading machines which may thread one end at a time or both ends at once. The threaded ends are doped with a mixture of tallow, graphite, and white lead; a coupling is screwed on one end and a thread protector on the other. They are then connected, one at a time, to a hydraulic testing machine which applies an internal pressure up to 2,500 p.s.i., depending upon the service required of the pipe. Any welding defects or other weaknesses show up under this treatment and any defective lengths are scrapped. As a final precaution against rusting in transit, the pipes are often coated with a protective covering which is sprayed on and dries rapidly. The finished pipes are measured, the smaller sizes bundled, the lengths and size stenciled on each bundle, or on each length, and loaded into cars for shipment.

Lap-welding Process.—Lap-welded pipe is usually made in sizes ranging from 1¼ in. nominal pipe size to 24 in. actual outside diameter. The procedure used in rolling the skelp depends upon the size of the pipe being made.

Skelp for the smaller sizes is produced on a continuous mill like skelp for butt-welded pipe except that the edges are usually scarfed in the finishing rolls so that they will fit together when the skelp is bent into the form of a pipe. When the pipes are too large in diameter to be made from skelp, sheared or universal

plates are produced by the usual methods, universal plates being used when their widths are applicable. If sheared plates are used, the shearing operation must be done very accurately. A rotary shear is placed on each side of the delivery table and a magnetic device used to hold the plate stationary while the shears travel the length of the plate. The distance between the shears can be very accurately adjusted to cut within close limits. The plate is then cut to the desired lengths, inspected, and transferred to the pipe mills where it is scarfed on emerging from the bending

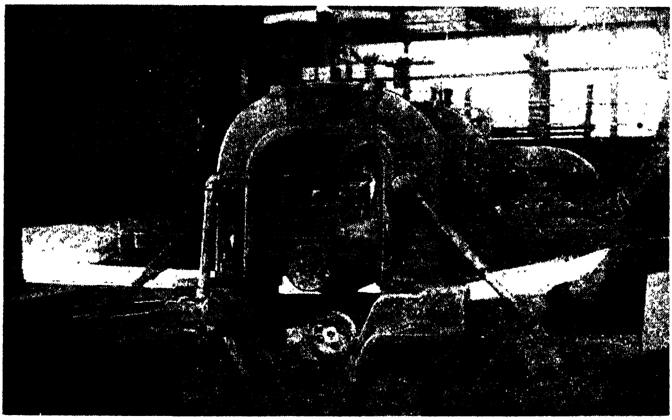


FIG. 5-XV.—Scarfing rolls on the discharge side of the bending furnace. (*Courtesy of Jones & Laughlin Steel Corporation.*)

furnace. In some cases the continuous skelp for the smaller sizes is also scarfed at the pipe mills.

As the lap-welding process is usually carried out, the various steps are preheating, scarfing, bending, heating for welding, welding rough sizing, straightening, final sizing (scale breaking), straightening, cutting, and finishing. No one set of equipment for making lap-welded pipe is able to make all the sizes possible in this material, but any unit is designed for a limited range of sizes. Several duplicate units are installed when the whole range of sizes is to be made. For example, one mill may be designed to weld pipe from 2 to 8 in. in diameter; another in the range from 6 to 16 in. in diameter, and so on. In any one plant, the different units vary little except in size of the equipment.

For pipe up to about 12 in. in diameter, the following procedure is used in bending the pipe preparatory to welding. The

flat skelp is charged into the bending furnace from a traveling charging machine in much the same manner as in charging skelp for butt welding, except that skelp for pipe under 4 in. in diameter is sometimes charged in piles. The furnace itself is not much different from the butt-welding furnace in construction except that the bottom is lined with sand and gravel and the furnace is maintained at a temperature between 1300 and 1450°F. At the delivery end of the furnace a two-high or a three-high stand of scarfing rolls is mounted close to the furnace on a track so that it can be moved along in front of the furnace opening. If the skelp is already scarfed, this stand of rolls is omitted and the bending die and its carriage are substituted in its place. In case the scarfing rolls are used, a strip is pushed out of the furnace until it can be grasped by the rolls which bevel the edges and pull it the rest of the way from the furnace. Directly behind it is placed the bending die on its movable carriage, and the end of the skelp is grasped by a short pair of tongs which are then engaged with an endless chain. The tongs pull the piece through the cast-iron bending die, which is so shaped that it delivers the material in the form of a split cylinder with the scarfed edges overlapping and ready for welding. The large sizes that are apt to collapse in the welding furnace are further treated by tack-welding the scarfed edges together in two or three places.

Plate for pipe larger than about 12 in. in diameter is bent in rolls as the bending die is not readily applicable to such large sizes. The machine consists of two long horizontal rolls mounted side by side a short distance apart and a third one suspended above and between them. All the rolls are of slightly greater length than the length of pipe being made and are powered by an electric motor. Since the rolling surface of the top roll projects well down into the space between the other two, a plate passed sideways between the upper and the lower rolls will be bent almost into the form of a cylinder. At the end of the first turn, the edges are bent or pressed together and the piece given several more turns to shape it into a smooth cylinder. One bearing of the top roll is then removed, the roll being automatically supported at the other end, and the bent cylinder withdrawn from the top roll.

Still another method for bending the skelp is used on the small sizes and consists of eight or ten stands of small rolls

placed very close together in a tandem arrangement. In the first few stands the curvature is started and when it becomes pronounced, rolls bearing on the outside in the later stands close the loop and overlap the scarfed edges. This method is quite rapid and is carried out on cold skelp which is subsequently preheated in the bending furnace before charging into the welding furnace for welding.

The welding furnace is of the same length and approximately the same width as the bending furnace, and is placed beside it. The drawing end of the bending furnace is at the same end as the charging end of the welding furnace so that the bent skelp can merely be rolled down an inclined framework for charging into the welding furnace. In this way, the heat in the bent skelp is preserved by immediately charging it into the welding furnace. The welding temperatures will range, according to the grade of steel used, the same as those given under the butt weld operations. The furnace temperature, however, will run somewhat higher, ranging from 2600 to 2625°F. The furnace itself must be constructed of the best grade of silica brick to withstand the high temperature and the bottom is covered with gravel and broken chinaware. The bottom is inclined gently toward two shallow troughs side by side and extending the length of the furnace near the center. The bent skelp is charged near the sides of the furnace and is slowly moved down to one or the other of the troughs as it is heated. For the final heating period the bent skelp rests lap upward in this trough and with the end at the charging side of the furnace a little lower than the other in order to allow the liquid scale to flow away from the skelp. The proper welding temperature is reached when the scale melts and flows freely, but the welder should watch the furnace carefully in order to heat the piece evenly throughout. Any cool spots will not weld and any overheated areas result in lowered physical properties of the finished pipe. The welding furnace is served by a movable charging machine running on tracks in front of the furnace. It picks up the bent skelp at the end of the runway with a pair of large tongs, pushes it into the furnace, and deposits it upon the furnace bottom.

The lap-welding equipment is placed on the delivery side of the welding furnace. A movable carriage is provided on which are mounted a pair of rolls, a mandrel, and equipment for pulling

the mandrel rod out of the pipe after welding. The two-high stand of rolls is quite massive in construction, and a circular pass is cut in the rolls to receive the bent skelp. These rolls are within a foot of the furnace and are protected on the furnace side by a bell-shaped guide which directs the bent skelp between the rolls. A trough is placed on the carriage, which extends back from the delivery side of the rolls for a distance somewhat greater than the length of the pipe. A mandrel rod of about the same length as the trough is supported in the trough, over the end of which fits the mandrel head. The head is shaped like a short, blunt-nosed projectile and is commonly made of a high manganese steel containing nickel and chromium as addi-

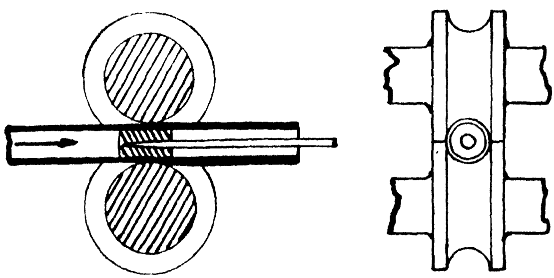


FIG. 6-XV.—Lap-welding rolls with welding ball and bent skelp in position.

tional alloying elements. The mechanism for pulling the mandrel bar out of the pipe consists of a small pair of rolls which are grooved to grip the rod. The assembly is shown in Fig. 6-XV.

In operating the equipment, the bar is pushed forward and a mandrel head or *welding ball*, as it is called, placed on the end of the bar. The bar is then pushed the rest of the way forward and locked in such a position that the welding ball is centered in the groove of the welding rolls. The carriage is then moved on its track until it is in line with the length of bent skelp which is ready to be welded, whereupon the charging machine pushes the piece, lap upward, into the guide until the revolving rolls grasp it. The rolls then propel the skelp rapidly between them and over the welding ball, welding the joint by the tremendous pressure produced. The rolls fix the outside diameter while the mandrel sets the inside diameter and removes the liquid scale from the inside of the pipe. The operation of welding does not occupy more than three or four seconds and

often only two seconds. The bar-pulling rolls are brought into play, the bar is withdrawn from the pipe which is then removed from the trough and passes down an inclined framework to the trough at the entrance to the sizing rolls. The welding ball drops off the bar when it is withdrawn and is picked up by a workman, cooled in water, and cleaned of scale. Another ball is placed on the bar as it again comes forward. The pipe is inspected in the trough and, if the weld is not satisfactory, the pipe is rolled down an incline on the side of the furnace opposite the sizing rolls to a conveyer which takes it back to be recharged into the welding furnace.

Satisfactorily welded pipe is put through a pair of sizing and crossed straightening rolls in succession. In the latter it is usually sprayed with water to keep the rolls cool and to cool the pipe. Since the pipe is still at a high temperature in the first sizing rolls, it is very difficult to fix the final size of the pipe. Therefore, owing to contraction on cooling, the pipe is allowed to cool to its critical temperature and the final sizing done in another stand of rolls, followed by a second straightening operation. This treatment removes any scale formed after welding and also tends to reduce the grain size of the pipe by working it during the cooling period. The finishing operations are, in general, of the same type as for butt-welded pipe and will not be considered here.

Zinc is widely used as a protective coating on the smaller sizes of pipe and pipe couplings. Two methods are in use for coating the pipe: the hot dip and the electrogalvanizing methods. In the hot dip process, the pipes are pickled, washed, and dipped into an alkaline bath to remove the last traces of acid. They are then dried and submerged in a long tank containing molten spelter (zinc) and a special flux. As soon as each pipe reaches the temperature of the bath, it is withdrawn up an incline to allow the spelter to flow from the inside of the pipe. As it is withdrawn, it is pulled through wipers which smooth out the coat and remove the excess zinc. At the same time, a jet of compressed air or steam is blown through the inside of the pipe to remove the excess spelter.

Electrogalvanizing consists in submerging the pipe in a large tank filled with a solution of zinc sulfate and passing an electric current through the solution. The pipes form the *cathode*, or

negative pole, and rods of zinc the *anode,* or positive pole of a d.c. circuit, the current passing from positive to negative through the solution. This action causes the deposition of an even coating of zinc on the metal. When steel couplings are being galvanized, a zinc anode is lowered inside each coupling so that the inside will be well coated. The thickness of the coat depends principally upon the time and the current density (the amount of current per unit of surface of the submerged pipe). The pipes must be pickled and washed before treatment.

Hammer Welding or Forge Welding Process.—Bent skelp larger than about 30 in. in diameter tends to collapse at the full heat of the welding furnace, owing to insufficient strength at that temperature. At the same time, pipe of much larger size than this is often desired and the hammer welding process is one method used in making these large sizes up to about 8 ft. in diameter. The process consists in scarfing the sheared plate, bending, heating, and welding the lapped joint, annealing, straightening, and finishing.

Carefully sheared plates are produced on a sheared plate mill, heated to a red heat, and run through a set of scarfing rolls which bevel the edges for lapping. The skelp is then bent on a machine much like that used for the large sizes of skelp to be lap welded, except that the machine is larger and consists of four rolls instead of three and is designed to bend the pipe more accurately. The welding machine consists of a small power hammer mounted in a stationary position over an anvil which is supported on a long, counter-weighted shaft which must be longer than the length of pipe welded as the pipe slips over this shaft. On the entering side of the machine, two specially designed gas burners are placed in a vertical position, facing each other. They are situated in line with the anvil and about 2 ft. in front of it for the purpose of heating the lapped joint to the proper temperature for welding, the joint of the pipe being passed between the burners. The pipe is supported on a moving carriage which can be adjusted in such a way that the joint of the pipe gradually moves between the burners and then between the hammer and anvil where the joint is welded and forged down to the same thickness as the rest of the pipe.

Since the metal adjacent to the weld is heated to quite a high temperature but not refined in grain by the hammer, it

retains a large grain size caused by the heating and is, therefore, a source of weakness. For this reason, the pipe is removed, charged into an annealing furnace and heated to just above the critical range to refine the grain, withdrawn, and again placed in the bending rolls. This machine now performs the function of a straightening machine and produces an almost perfect round. The pipe is then allowed to cool in air, the rough ends cropped off with an acetylene torch and then subjected to the necessary finishing operations to fit it for service, such as flanging and coating.

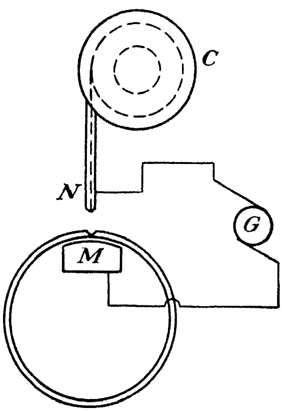


FIG. 7-XV.—Sketch showing the method of metallic arc welding. (*From Iron Age.*)

Electric Welding Process.[1]—Within recent years, electric welded pipe has invaded the field previously held solely by the forge welding methods already described. Electricity is now used to weld practically all sizes of pipe and tube, automatic or semiautomatic machines being used for the small and medium sizes and manual methods for the largest sizes. It is not to be inferred from this, however, that the old forge welding processes are disappearing because they are still used to a great extent. The investment in such mills all over the country was too great for them to be scrapped in favor of an innovation, and the existing plants were merely modernized in many cases by the introduction of electric charging machines and conveying equipment to speed up production and decrease costs. The electric welding methods have come to be competing processes, but that is about as far as it has gone at present.

Both the plastic and the fusion methods of electric welding are in use at the present time. The steps in the process consist of rolling the skelp or plate, scarfing, cold bending, welding, and finishing. The principles of some of the various methods will be covered first and followed by a description of a typical plant operation using the fusion process.

[1] The sketches reproduced in this section are from an article by R. E. Kinkead in *Iron Age*, **123**, 1410 (1929).

The fusion process of metallic arc welding is applied to pipe much in the manner shown in Fig. 7-XV. The pipe is scarfed so that when it is bent, the opening is semicircular in cross section. The electrode N is supported from an automatic head C which maintains the proper length of arc and feeds the electrode downward to the material without manual help. The mandrel M is designed as a current electrode and also to keep the weld metal from running through to the inside of the pipe. G represents the electrical meters which record the power used. The pipe is often held stationary and the automatic head moves uniformly along the length of the pipe, its travel being controlled automatically. In such machines, large, flux-coated welding rods are usually employed. If the pipe is so thick that one travel will not deposit the required amount of weld metal, several automatic heads are used which traverse the length of the seam in succession and lay down the required amount of metal. In other machines, the pipe is moved through and the heads are stationary.

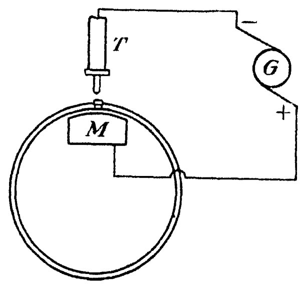


FIG. 8-XV.—Sketch showing the method of automatic carbon arc welding. (*From Iron Age.*)

The machine-driven process in which the carbon arc is used is illustrated in Fig. 8-XV. The filler material is laid on the seam in the form of a rod or strip. The mandrel M provides the current connection and is notched under the joint to allow the weld metal to form a slight protrusion on the inside of the pipe. The edges are not butted tightly together and the carbon arc, in traveling slowly along the seam, melts the filler material and the edges of the pipe, forming the weld. An atmosphere of non-oxidizing gas is maintained around the arc by one of many methods, and the arc is stabilized by a strong magnetic field at T which is concentric with the vertical axis of the electrode. Gas welding is sometimes used to weld pipe in machines that operate along the same principle as carbon arc welding except that one or a succession of gas torches takes the place of the carbon arc. An automatically fed welding rod is sometimes used instead of the filler strip.

The plastic-type resistance-welding method is applied to pipe in the manner shown in Fig. 9-XV. The process is a continuous one in which the rolls *RR* pull the bent skelp through the machine and squeeze the edges together. The small rolls *WW* are connected to the low-voltage side of a transformer and conduct the heavy current to and from the pipe in the vicinity of the joint.

The advantages of the electric welding methods lie in the fact that it is not necessary to heat the entire piece in order to weld it. In the forge welding methods, with the exception of hammer welding, the entire strip must be raised to the full

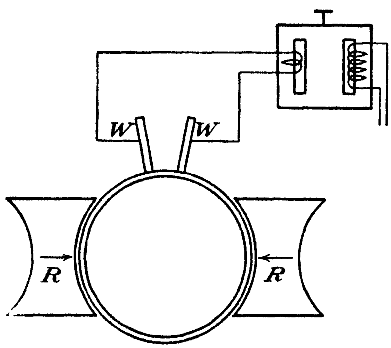


FIG. 9-XV.—Sketch showing the method of machine welding pipe by the electrical resistance method. (*From Iron Age.*)

welding heat while only a very small portion of the piece actually enters into the welding operation. The electric welding methods all localize the heat at the surfaces to be welded and thus conserve heating costs, even though the cost of electric heat is higher than that of gas or oil. In the resistance method, all of the heat produced is generated in the metal being welded; in the carbon arc process, about 60 per cent of the heat is produced within the metal to be welded; while in the metallic arc method, approximately 85 per cent of the heat is produced in the pipe and welding rod. The efficiency of these methods is, therefore, quite high and is an important reason for their widespread use. Another important advantage of the electric processes is that the skelp is not scaled in the process of being manufactured into pipe and will preserve a clean rolled finish throughout the subsequent steps. This eliminates the metal loss as well as the necessity of scale-breaking rolls.

In one typical plant installation,[1] the plate travels through a straightening machine and is then dried by gas jets. One side is then elevated until the plate makes an angle of 45 deg. with the horizontal and enters the blasting machine. In this step, the lower face of the plate is blasted with a large number of very small steel shot (0.02 in. in diameter), thus removing all scale and leaving the surface clean. The plate is again lowered to the horizontal and the underside of the edges beveled in a special machine. The plate is clamped in a stationary position and two cutting carriages move along the edges. Each carriage has 14 tools set so that each succeeding tool takes a cut slightly deeper than the preceding one. From the scarfing machine, the plate passes to the first of two hydraulic bending presses. This press first crimps the edges and then forms the plate into a preliminary round section. This first press is of 750 tons capacity while the second, which completes the bending, is of 10,000 tons capacity. Since the last pass leaves the piece with the edges an inch or a little more apart, the bent skelp is tack welded about every 2 ft. along its length, the piece being squeezed together by air-operated clamps during the welding. This operation is carried out merely to hold the edges in proper relation to each other and the effects are entirely removed by the final welding operation.

The bent and tack-welded skelp is now ready for the welding operation. This is conducted in one of many welding machines, each of which take about 600 amp. at 32 volts. The welding rod is held stationary and the pipe moved along under it on a traveling carriage. A stationary *horn* or mandrel is placed underneath the joint to be welded and this part is water cooled to prevent overheating. Bare welding rod, 3/16 in. in diameter, is used by the machine. When the pipe enters the machine, it passes under a hopper which deposits a special flux on the seam in a ridge 3/4 in. high and about 1 1/2 in. wide. The welding rod is suspended a few inches ahead of the hopper and the welding operation takes place under the layer of flux that protects the weld from oxidation and ensures slow cooling afterward. A suction device, placed about a foot after the welding rod, removes the excess flux. The pipe is passed along on its carriage at a

[1] Koon, S. G., *Iron Age*, **127**, 1502 (1931).

uniform rate and a 40-ft. length of pipe is welded in one continuous operation.

The welded pipe is slightly oversize, is not quite round, and is later pressed to the correct shape and outside diameter in a 10,000-ton hydraulic press. The excess weld metal is taken off the ends for a distance of about 8 in. so that a pipe coupling

FIG. 10-XV.—Pickling blooms before rolling them into billets for the seamless mill. (*Courtesy of Jones & Laughlin Steel Corporation.*)

may be used. The ends are faced and beveled in special machines that work on both ends of the pipe at once, after which the pipes are tested hydraulically before shipment. This plant is capable of making pipe from 14 to 30 in. in diameter in 40-ft. lengths and in sizes from 24 to 72 in. in diameter in 20-ft. lengths.

Seamless Process.—Another method of making pipe and tube which has made serious inroads into the field formerly held exclusively by the forge welding processes is that in which a hole is pierced longitudinally through a solid hot bloom or billet to

form a *seamless* tube. This method came into use about 1900. Since that time it has been extensively improved until, at present, it is capable of making tubular products in sizes up to 24 in. O.D. Cold drawing of the hot finished material will produce smaller sizes, smoother finish, and more accurate dimensions than is possible on hot finished tube, as well as modifying the physical properties.

Several different methods are in use for producing the finished tube after the hole is once pierced through the piece. The most

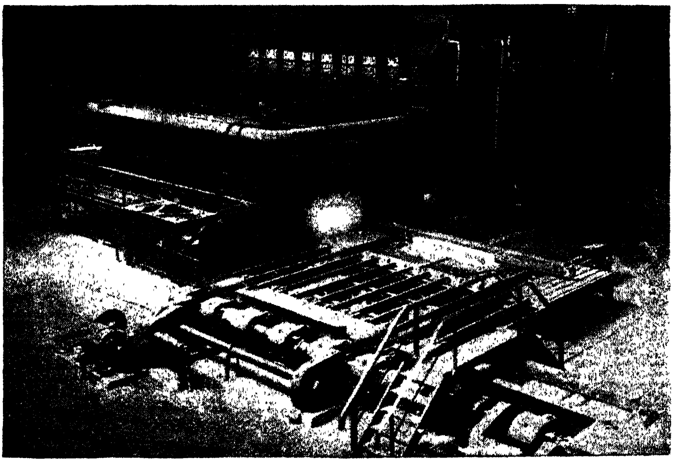


FIG. 11-XV.—Continuous heating furnace for reheating the pickled blooms. (*Courtesy of Jones & Laughlin Steel Corporation.*)

important is known as the *automatic mill* or the *plug mill* method, while the *Pilger* process is used to some extent in this country and very widely in Europe. Finally, the *Foren* process is used in the production of small sizes of hot-finished tubes. These methods will be described in that order.

The automatic seamless mill consists of a centering machine, continuous heating furnaces, a piercing mill, an expanding mill (if sizes larger than about 7 in. in diameter are to be made), a plug mill, a reeling machine, and some type of mill for final sizing operations. Carefully cast ingots of killed steel are rolled to bloom sizes ranging from about 8 by 8 in. to 14 by 14 in. The blooms are cooled to room temperature, pickled (Fig. 10-XV), carefully inspected, and all surface defects chipped out. The

blooms are then reheated to rolling temperature (Fig. 11-XV) and rolled to circular billets (Fig. 12-XV), the sizes of which vary with the size of the pipe being made but are considerably smaller in diameter and shorter than the dimensions of the finished pipe. A hydraulic machine then punches a hole about 1 in. deep in the center of one end of each billet, after which the billets are charged into a continuous furnace where they are heated for piercing.

There are two piercing mills in use, one being known as the *Mannesmann* or roll piercer and the other as the *Stiefel* or disk

FIG. 12-XV.—Mill for rolling round billets from the reheated blooms. (*Courtesy of Jones & Laughlin Steel Corporation.*)

piercer. Both operate on exactly the same principle and the former is the more popular type at the present time. The Mannesmann mill consists of two heavy rolls and a mandrel rod equipped with a piercing point or head, the relative sizes and positions of the parts being shown in Fig. 13-XV. The rolls are about 24 in. long in the face and from 32 to 40 in. in diameter, the dimensions varying with the size of tube being made. Their shape resembles a piece cut from the middle of a very large spindle with a flat portion about 1 in. long at the middle. From this flat portion, the roll tapers toward each end at an angle of from 3 to 10 deg. When these rolls are placed in their housings, they lie side by side with their axes inclined in opposite directions, each at an angle of from 6 to 12 deg. with the line of travel of

the billet, so that the rolls cross each other at their centers. The angularity of the roll faces is necessary to produce the play of forces required to effect the piercing while the amount of angle at which each roll is inclined from the line of travel of the billet fixes the speed at which the billet travels through the mill. The rolls are usually of special steel, are connected to their power source by a special type of universal joint, and can be adjusted laterally in their housings to accommodate different sizes of billets. The distance between the rolling surfaces at the centers is a definite amount less than the diameter of the billet to be pierced. As shown in Fig. 13-XV, the mandrel rod is on the delivery side of the mill and is longer than the length of pierced billet being made. It is water cooled and smaller in diameter than the piercing point that fits over its end. The rod and mandrel are revolved in the same direction as the billet and at the same speed and are mounted on a carriage which has a rapid forward and back movement in order to pull the rod out of the pierced billet and move it forward again to receive the next one.

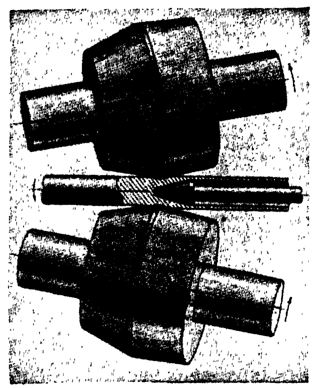


FIG. 13-XV.—Sketch of a Mannesmann piercing mill. (*Courtesy of the American Society for Metals.*)

With the rolls revolving at constant speed and the piercing point revolving but centered in the space between the rolls with its end just past the center of the rolls, the mill is ready to receive a heated billet. The billet is ejected from the heating furnace to a trough on the entering side of the mill. A rod actuated by either a hydraulic or an air cylinder pushes the billet, punched end first, into the mill. The rolls immediately grasp the billet, revolve it rapidly, and pull it slowly forward. At the same time they open a cavity along the center of the billet and force the metal over the piercing point. The pierced billet emerges from the mill in the form of a thick walled tube considerably longer than the billet, somewhat rough on its surface, but of fairly uniform wall thickness. The entire operation consumes less than one minute. The electrically operated carriage

is then moved back, pulling the mandrel rod out of the tube, the tube is kicked off the delivery trough of the mill, and the rod is brought forward for another billet. When the rod is removed from the tube, the piercing point drops off and is quenched in water by a workman, who replaces it with a cold one as the rod again comes forward. The pierced tube rolls down an inclined table to the next step in the process. The piercing mill in operation is shown in Fig. 14-XV.

The action by which the piercing mill is able to force a billet over a mandrel, thus forming a seamless tube, is rather difficult

FIG. 14-XV.—The Mannesmann piercing mill in operation, delivery side. (*Courtesy of Jones & Laughlin Steel Corporation.*)

to explain. The mandrel is not forced through the metal, but the rolls cause the metal to flow spirally over the mandrel. It is a known fact that a center cavity can be opened in any round plastic solid body by pressure exerted at opposite points on the circumference and the same action occurs in the piercing mill. As the billet enters the mill, the rolls grasp it at opposite points on its circumference while it is yet about 4 in. from the center of the rolls. As they draw the billet forward, the compression increases owing to the angularity of the rolls.

The amount of stress on the billet is controlled by the roll setting; the closer the rolls the greater will be the reduction and,

hence, the greater the stress at the center. When the stress is great enough to cause rupture, an irregular cavity will be formed. If this irregularly shaped cavity is rolled over the point after forming, a tube will be produced that is seamy on its inside surface. Thus the mill operator is careful that the rolls are not too close together and that the point is advanced far enough into the mill that no breaking of the metal can occur before contact is made with the point. The piercing point does very little work since the rolls themselves open and enlarge the central cavity.

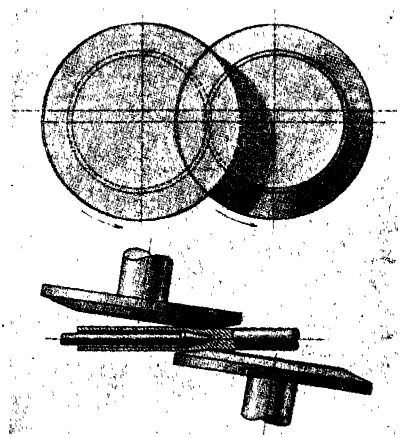


FIG. 15-XV.—Sketch of a Stiefel piercing mill. (*Courtesy of the American Society for Metals.*)

The piercing point smooths out the cavity, fixes its diameter, and keeps it centered with respect to the circumference of the piece.

The Stiefel piercing mill, shown in Fig. 15-XV, operates on the same principle as the Mannesmann mill. The rolling surfaces are two disks, some 30 in. in diameter, which are beveled at an angle of 7½ deg. for a distance back from the edge of nearly one-half the radius. The disks, which rotate in the same direction at the same speed, are mounted on the ends of, and perpendicular to, two heavy parallel shafts which are gear driven from a main driving shaft. The disks overlap to only a small extent, are parallel, and are inclined to the direction of travel of the billet. At their point of nearest approach, the disks are separated by a distance slightly less than the diameter of the billet being pierced. Troughs are provided on both sides of the mill

for supporting the billet, and the rotating water-cooled mandrel rod and piercing point is placed in the delivery trough. The operation of piercing is conducted on this mill in exactly the same manner as with the roll piercer, and the action on the billet is also the same. The disks have been found to be more difficult to keep in shape than the rolls of the Mannesmann machine. For this reason, as well as others, the roll piercer is preferred.

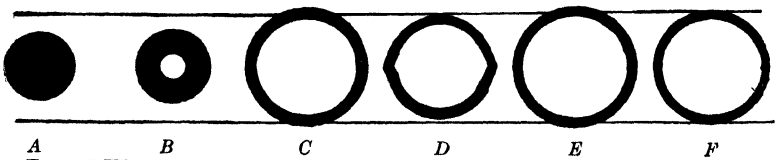


FIG. 16-XV.—Sketches of a cross section of a piece after various steps in the production of the finished seamless pipe. *A*, original billet; *B*, after piercer; *C*, after expanding mill; *D*, after plug mill; *E*, after reeler; *F*, after sizing mill.

The pierced blank emerging from either type of piercing mill is in the form of a heavy walled tube of much greater length and of greater outside diameter than before the operation (see Fig. 16-XV). The next step in the process depends upon the size of the pipe being made. If the diameter of the finished pipe

FIG. 17-XV.—Mannesmann mill for expanding the pierced billet. The insert shows the working parts. (*Courtesy of Jones & Laughlin Steel Corporation.*)

does not exceed about 7 in., the pierced blank is sent directly to the plug mill. If a larger size is to be made, the blank is put through a second piercing mill of the Mannesmann type, called the *expanding mill*, where the diameter is increased and the wall thickness reduced. The mill is operated exactly as in the first

piercing operation, the only difference being in the relative sizes of the piercing points and the distances between the rolls. The difference in size and shape of the mandrel can be seen by comparing the inserts in Figs. 14-XV and 17-XV. The effect on the pierced blank is shown in Fig. 16-XV.

From the expanding operation, the piece passes directly to the *plug mill* (Fig. 18-XV) where the wall thickness is decreased to about the finished value. The plug mill is a two-high mill of conventional design containing several round grooves of different sizes so that greater flexibility may be obtained without roll

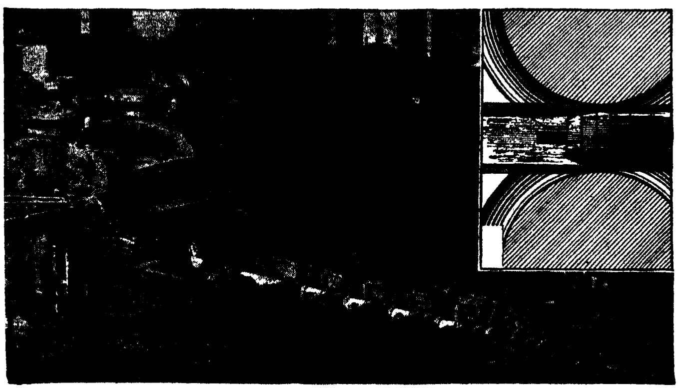


FIG. 18-XV.—The plug mill in operation. The insert shows the working parts. (*Courtesy of Jones & Laughlin Steel Corporation.*)

changes. A stationary water-cooled mandrel rod and plug are supported on the exit side of the mill in such a position that the plug is suspended in the appropriate groove in the rolls in the position shown in the insert. The difference in the shape of the plug from that of the piercing point can also be seen. With the mandrel and plug in position, the blank is fed into the correct groove, causing a decrease in outside diameter and wall thickness. When the tube is entirely rolled out over the mandrel rod, the stripper rolls, which are placed very close to the working rolls on the exit side, are brought together until they grasp the tube and pull it through to the entering side of the mill. No work is done by the stripper rolls, their purpose being merely to push the blank through the mill on the return pass. By this device, both the working and the stripper rolls are driven in one direction only (but in opposite directions in relation to each other); thus

avoiding the necessity of a reversing motor for the working rolls. Two passes are usually made through the plug mill in the working direction, the tube being turned 90 deg. by hand between the passes. After the first pass, a workman removes the plug, cools it in water, and replaces it with one of larger size for the final pass. The product of the plug mill has approximately the correct wall thickness and length but is slightly undersize and is not perfectly round while the inside and outside surfaces are not smooth (see Fig. 16-XV).

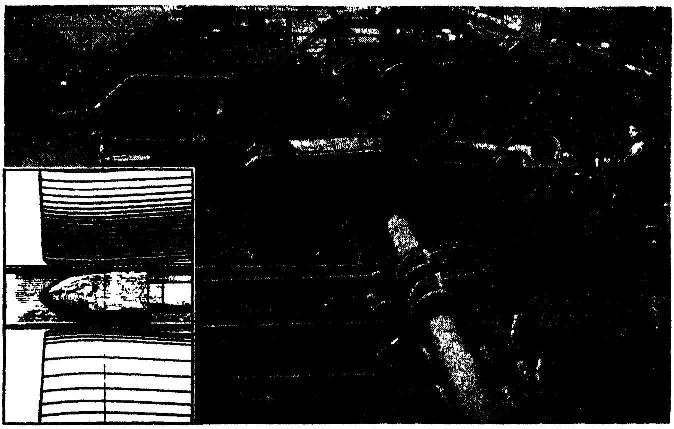


FIG. 19-XV.—The reeling mill in operation. The insert shows the working parts. (*Courtesy of Jones & Laughlin Steel Corporation.*)

The irregularities are mainly eliminated in the reeling operation. Two reelers are necessary as their operation is about one-half as rapid as that of the piercers and the plug mill. Both are identical in size and operation and tubes from the plug mill are routed to either of them. The *reeler* shown in Fig. 19-XV utilizes the principle of crossed rolls causing the tube to be rotated rapidly as it is slowly drawn through. The rolls are flat, however, and not tapered as in the piercer, but a mandrel rod and plug are used. The arrangement of the rolls and the shape and position of the plug may be seen in the insert. The action of the reeler on the tube is to expand the tube slightly, burnish the inside and outside surfaces to make them smooth, and accurately fix the wall thickness at the desired value. Some pressure is used and the plug is slightly larger than the desired final inside

diameter, the product of the reeler thus being slightly oversize but of finished surface and correct wall thickness.

The final step in the production of hot finished tubes or pipes is again dependent upon the desired size of the finished material. Most of the tubes are put through a *sizing mill* which consists of a single two-high stand or of several stands closely arranged in tandem, five stands being about the maximum. If more than a single stand is used, the axes of the rolls of all stands are inclined at an angle of 45 deg. to the horizontal and alternate stands are

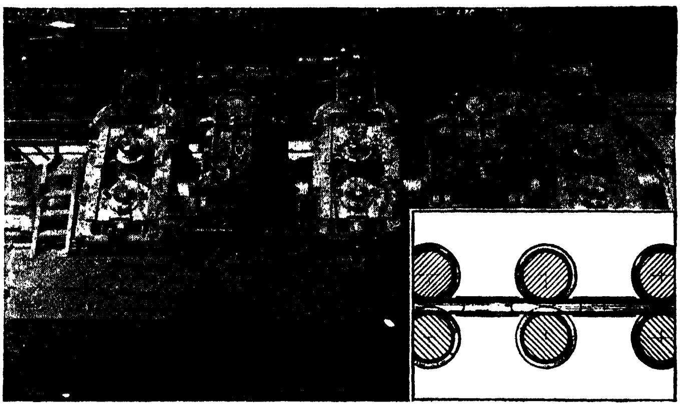


FIG. 20-XV.—A mill for sizing the reeled tube. The insert shows the position of the rolls. (*Courtesy of Jones & Laughlin Steel Corporation.*)

inclined 90 deg. to each other. The object of this arrangement is to have alternate stands working on the tube in directions at right angles to each other and at the same time get away from the necessity of having vertical stands. One such five-stand mill is shown in Fig. 20-XV. The mill operates in the same manner as any continuous mill, grooves of decreasing size being cut in successive stands to reduce the diameter of the tube to the desired final value (allowance is left for contraction on cooling). The speeds of rotation of the various stands are so regulated that no decrease in wall thickness results, the increase in length compensating exactly for the slight decrease in diameter. All the above operations are carried out on one heating since the production of the hot-finished tube from the heated billet is effected very rapidly.

A seamless tube about 3 in. in diameter is about the smallest product of the reeling machine that it is practicable to produce. As smaller sizes than this are often desired, the tube from the reeler is reheated in a continuous furnace and put through what is often called a *sinking mill,* in which it is reduced in size by the desired amount. This mill is constructed like the continuous sizing mill described above, except that it contains as many as 16 or more stands of constantly decreasing groove diameter. In fact, in some plants a single horizontal two-high stand which reduces the reeled tube the slight amount necessary to arrive at the desired diameter is called a sizing mill, while the continuous mill is called a sinking mill or a reducing mill, regardless of the number of stands, as long as it consists of more than one. Obviously, the greater the amount of reduction in outside diameter necessary, the more stands required. By the use of the sinking mill, a 3-in. tube can be reduced to a tube of 1½ in. in outside diameter without changing the wall thickness. The sinking operation also brings the pipe to the exact final size, at least within hot finishing tolerances.

The finishing operations are about the same as those used on pipe made by other methods except that more care is taken with seamless because of the greater stresses it is required to stand in service and the more rigid specifications under which it is produced. The tube is slowly cooled after sizing by rolling it along a long cooling rack. The chain-driven fingers that roll it along have rollers where they come in contact with the pipe to keep from marring the surface. The material is then cold straightened in a roller straightener which also removes the scale. The material is then inspected, cut to size, threaded, tested hydraulically, given a light protective coating to prevent rusting during transportation, and loaded for shipment.

The *Pilger* process differs in several important respects from the one already described for producing seamless pipe and tube. In the first place, round ingots are bottom cast of killed steel and, after inspection, are charged directly into heating furnaces serving a heavy type of Mannesmann piercing mill. In the automatic process as small a billet as is practicable for the size of tube being produced is used and this is expanded to the final size. The Pilger process starts by piercing an ingot, the pierced blank being of larger size than the desired finished tube. The

operation of piercing is exactly the same as described previously and need not be discussed further at this point. Without reheating, the blank is conveyed to the entering trough of one of two Pilger mills, two being necessary to keep up with a single piercing mill.

The Pilger mill consists of two rolls with parallel axes mounted and operated as in an ordinary rolling mill; it differs in that the process is nearer to one of forging than rolling. The rolls are grooved to produce a circular pass but the pass is cut away through about half of the circumference of each roll, as can be seen in Fig. 21-XV. The result is that with each revolution, the

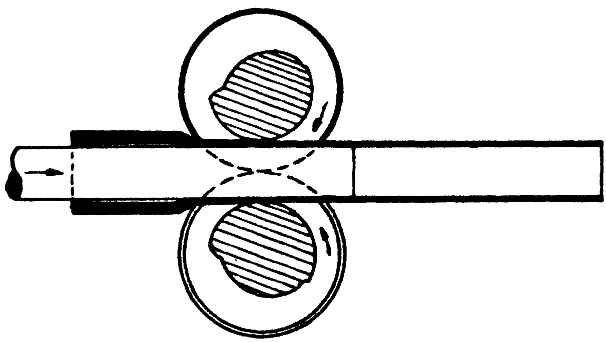


FIG. 21-XV.—Cross section of the working parts of the Pilger mill.

portion of the pass not cut away strikes the tube a definite and severe blow. When the pierced blank comes to the mill, a round bar of steel, 10 ft. long, is inserted in it. This bar or mandrel is of the same diameter as the inside of the tube after it emerges from the mill. The mandrel is carried on the forward end of a plunger working in a pneumatic cylinder, which in turn is moved by two large hydraulic cylinders. The hydraulic cylinders, by being connected to the pneumatic cylinder, form a powerful hydraulic ram which moves slowly but steadily forward, pushing the mandrel through the pierced blank and supporting it in the actual operation. Because the direction of rotation of the rolls is against the tube rather than with it as in ordinary rolling, the tube is thrown back while in working contact with the rolls.

The forging action of the rolls driving the tube backward causes the air to compress in the pneumatic cylinder but, as

the rolls revolve and again bring their cutaway section into the tube space, this compressed air forces the plunger, carrying the mandrel and tube, forward again for the next stroke of the rolls. The hydraulic cylinders behind the pneumatic one push the tube and mandrel forward a slight distance farther for the rolls to work on a small amount of new section on their next blow. The pneumatic cylinder thus acts as a spring in taking up the force of the blow while the hydraulic cylinders continually force the tube forward for succeeding blows. A mechanical device automatically rotates the mandrel and tube 90 deg. between the forging blows of the rolls. The tube thus progresses through the rolls in a halting manner but the forward stroke is longer than the backward push given by the rolls. The size of the mandrel fixes the inside diameter of the forged tube while the setting of the rolls determines the outside diameter and the wall thickness. The extension of the tube, owing to its decrease in size, takes place in the direction of travel of the material through the mill as shown in the sketch. The forged tube is purposely left oversize.

When the above operation is completed, a mechanical stripping device on the roll housing holds the tube in a stationary position while the mandrel is withdrawn by the hydraulic cylinders. The mandrel must be cooled before it can be used again, for which reason several mandrels are provided and used in succession. The Pilger process makes a very long tube as the length of the mandrel bar does not limit the length of the tube as in the plug mill. Consequently, a decrease in scrap loss is obtained by piercing and forging down an entire ingot, after which the crop ends are cut off and the long length cut into two or three tubes. The tubes are reheated, put through the reeler and sizing mill in succession, then cooled, straightened, and finished like any other seamless tube.

The advantages of the Pilger process are that by piercing a cast ingot, the rolling operations are done away with and that the process will make a tube of almost unlimited length, depending only upon the size of the tube and the amount of metal in the ingot. Tubes over 130 ft. in length have been made. Also, the Pilger mill is capable of making the larger sizes of tubes (up to 20 in.) thus taking the place of both the expanding and plug mills of the automatic process. In spite of these advantages,

the method is not used very much in this country but is very popular in Europe. The process has several important disadvantages which limit its use in this country. The output of the Pilger mill is much less than that of the plug mill while the cost of rolls and mandrel replacement and upkeep in general is much greater. The plug mill produces a more uniform and better finished tube and can produce larger sizes if the expanding mill is used.

A recently installed mill[1] of new design is used at present in the production of small sizes of seamless products (1 to 4 in. in diameter) but may be used on larger sizes in the future. Billets are heated and pierced in the ordinary manner and are then fed immediately to the Foren mill. This mill operates on the principle of rolling the tube with a long, carefully finished mandrel rod inside it to maintain the desired inside diameter and more accurately adjust the wall thickness and perfection of roundness of the tube than is possible in either of the previously described processes. As the pierced billet arrives at the entering trough of the mill, a cold mandrel rod is run through the pierced blank to a point where the blank is about one-third of the length of the rod from the forward end. The pierced blank and mandrel are then pushed into the first of five two-high stands of rolls, three of which are horizontal and two vertical but all in a close coupled tandem arrangement. This group is called the "squeezer" as its purpose is to fit the tube to the mandrel. Immediately following the above five stands are 17 working stands in tandem on 21-in. centers, each stand being driven by an individual electric motor. Successive stands are inclined at different angles so that the tube is worked at many different points on its circumference in succession. For example, the first stand of working rolls is inclined at an angle of 22½ deg. to the horizontal. As the tube leaves this stand, it is slightly elliptical and, therefore, the next stand is at a 90-deg. angle to the first. This produces an ellipse on the opposite axis while the third pair of rolls form the tube to a true cylinder. Each succeeding group of three stands repeats this procedure, thus constantly elongating the tube and reducing its wall thickness by using smaller grooves in the rolls. Following the working stands is a group of four stands whose purpose is to bring the tube to a perfect circle and release

[1] FISKE, R. A., *Iron Age*, **133**, No. 11, 24 (1934).

the grip of the tube on the mandrel. As it emerges from the mill, the mandrel is completely covered by the tube, except for a short distance at the rear end. As this trailing end of the mandrel clears the mill, it is gripped by a clamp while a pair of rolls grip the tube and pull it off the mandrel, the latter being subsequently cooled and sent back for another trip through the mill. Two sinking mills are provided to produce very small sizes, if desired. The tubes are then cooled, straightened, and finished in the usual manner.

This process has the advantages of producing lengths up to 100 ft. with no scratches on the inner surface as always occur in plug mill products. A surface finish is obtained which is said to be as good as can be obtained by cold-drawing. The speed of operation is very rapid as six 35-ft. tubes can be passed through the mill every minute. All thicknesses from ½ in. to 20 gauge can be produced by screw-down adjustments and different mandrel sizes, while different outside diameters require roll changes. More accurate wall thicknesses and perfection of shape can be obtained by this method than by any other hot-finishing mill.

In the production of short lengths of large diameter seamless tubes, the *cupping process* is often used. This consists in placing a hot steel plate or blank over the lower die of a hydraulic press, the center of the die having a circular hole in it. A hydraulic ram smaller in diameter than the die hole pushes the plate down into the hole, thus forming a closed end seamless tube. Usually, several such operations are required to draw out the tube completely, after which the closed end is cut off. Previous to the invention of the piercing mill this was the most used method of making seamless products.

Cold-drawing operations are carried out on some seamless tubes for various reasons—a smaller cross-sectional area may be desired, closer dimensional tolerances demanded, a better finish, or greater strength. Cold-drawn seamless is known to the trade as "mechanical tubing." Hot-finished tubes are pointed, pickled, rinsed, and thoroughly coated, both inside and out, with a special lubricant designed to minimize friction. The mechanism for drawing the tube is shown in Fig. 22-XV. The pointed end of the tube is pushed through the circular die, the mandrel adjusted in place, the jaws clamped on the end of the tube, and the hook

dropped over a link in the endless chain. The power-driven end sprocket pulls the tube between the die and centered mandrel, thus reducing the outside diameter and wall thickness of the tube and increasing its length. The speed of operation varies from 25 to about 60 ft. per min. and the reduction in cross-sectional area per pass may vary up to 50 per cent, depending upon conditions. It is usually necessary to heat-treat the tube to restore ductility and then pickle it again after each drawing operation. This is accomplished by annealing in either a continuous furnace or in a specially designed electric furnace in which the tubes are not oxidized.

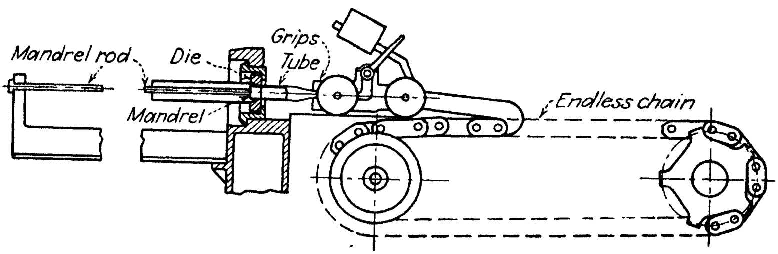


FIG. 22-XV.—Drawing of the mechanism for cold-drawing seamless tubing. (*Courtesy of the American Society for Metals.*)

Shop Fabricating.—This particular process involves the shaping of flat-rolled material into tubular form with the subsequent joining of the ends by mechanical means.

Lock-bar Pipe.—This type of tubular product is processed from plates, the longitudinal edges of which are planed and upset. The plates are then curved to the desired radius, after which the edges are engaged in the grooves of an H-shaped lock bar and closed by cold pressing to form a tight longitudinal joint. This method of processing is employed only for pipe 20 in. or over in outside diameter.

Riveted Pipe.—This type of tubular product is a shop-fabricated straight-seam pipe, made from plates that are cold-shaped into cylindrical form, with the seams joined by riveting. This method is used for pipe 14 in. or larger.

Classification of Tubular Products by Grades and Uses.—The following discussion pertains to the more common grades of tubular products and their uses. For complete specifications on the different grades discussed, the reader is referred to the

standard specifications as published by the manufacturers and technical societies.

Conduit Pipe.—This product is intended for fabrication into rigid conduit for use in the protection of electrical wiring systems.

Drive Pipe.—This type of pipe is used in gas, oil, or water wells for driving into the ground or for forcing into a drilled hole to prevent caving of the walls.

Ice Machine Pipe.—This grade of pipe, which is also known as "refrigeration pipe" and "ammonia pipe," is used in the refrigeration industry. It is suitable for coiling, bending, and end-to-end welding.

Large Diameter Pipe.—This grade is intended principally for water lines but is also used for conveying gases and liquids or solids in suspension.

Line Pipe.—This pipe is used principally for conveying gas, oil, or water.

Pressure Piping.—This grade of pipe as distinguished from "pressure tubing" is used for conveying fluids at normal or elevated temperatures or both, but not subjected to external heat application.

Structural Pipe.—This grade is used only as structural members for fabrication, etc., and is not intended for conveying gases or liquids or for pressure purposes of any kind.

Water-main Pipe.—This grade is used for conveying water for municipal and industrial purposes. In application these lines are designated as flow mains, transmission mains, force mains, water mains, or distribution mains. The mains are generally laid underground.

Water Well Pipe.—This grade of pipe is divided into five classes known, respectively, as water well casing, water well drive pipe (for driving water wells with short rigs or by hand sledging), water well pipe, water well reamed and drifted pipe (reamed and drifted to ensure proper clearance for pump plunger), and water well special well driller's pipe (for driving wells).

Oil Country Tubular Goods.—Oil country tubular goods is a collective term applied in the oil and gas industries to three kinds of pipe used in wells: casing, tubing, and drill pipe.

Casing.—Casing is used as a structural retainer for the walls of oil or gas wells, to exclude undesirable fluids, and to confine and conduct oil or gas from productive subsurface strata to ground level.

Tubing.—Tubing is used within the casing of oil wells to conduct oil to ground level.

Drill Pipe.—Drill pipe is used to transmit power by rotary motion from ground level to a rotary drilling tool below the surface, also to convey flushing media to the cutting face of the tool.

Pressure Tubes.—This class of tubes, as distinguished from pressure piping, is used to convey fluids at elevated temperatures or pressures or both, and is suitable to be subjected to heat application. This class is subdivided into boiler and superheater tubes, oil-still tubes, heat exchanger and condenser tubes.

Boiler and Superheater Tubes.—This type of tube is used in various types of steam-generating apparatus where they are subjected to pressure by water or steam at elevated temperatures either internally or externally.

Oil-still Tubes.—This class is used for carrying oil or vapors at elevated temperatures and pressures in various types of oil refining equipment in which the tube is subjected externally to furnace temperatures higher than that of the contained fluids.

Heat Exchanger and Condenser Tubes.—These are used in various types of heat-transfer apparatus in which the walls of the tube act as a heat-transfer medium between two fluids of differing temperatures.

Mechanical Tubing.—This type of tubing is used for such a variety of mechanical purposes that it is impracticable to make a subdivision into classifications. It is generally made in special sizes and shapes and to special tolerances. It may be either hot-finished or cold-drawn.

Suggested Questions for Study and Class Discussion

1. Describe briefly the manufacture of butt-welded pipe.
2. Describe briefly the manufacture of lap-welded pipe, showing the differences from butt welding with regard to the methods used.
3. What electric welding methods are in use for making pipe? What are the advantages of each method?
4. Describe how the Mannesmann piercing mill is able to form a rough tube from a solid billet.
5. Describe the method of making large seamless tube by the automatic mill process.
6. Give a description of the Pilger process. Discuss the advantages and disadvantages of the process.
7. Describe the method of cold-drawing seamless tube. What advantages are to be obtained by cold-drawing?
8. Make a list of the various common applications within the given pipe classifications.

CHAPTER XVI

FORGING PRACTICE

The principles of steel forging have been sufficiently covered in a previous chapter and need not be discussed further at this time. The details of the methods used in forging vary almost as widely as the range of products produced and, for that reason, a detailed discussion of forging technique is out of the question. There are, however, several general methods of reducing the cross-sectional area of steel sections and producing certain simple shapes under the press or hammer that merit description while some general precautions require emphasis. The essential requirements of drop forging work will also be briefly discussed. The above points for discussion by no means cover the entire field of forging practice, but they will give the student some insight into the methods used and the difficulties involved in producing forgings.

As a rough generalization it may be said that heavy forgings are produced on a forging press, medium sized forgings under the double-acting steam hammer, and light forgings by means of the drop hammer or forging machine. With this general viewpoint in mind, the methods used in making heavy forgings by means of the hydraulic press will be considered first.

Press Forgings.—Heavy forgings are produced for a multitude of uses in which the superior physical properties inherent in press-forged steels are desired. Among these uses may be mentioned ship propeller shafts, large cranks, oil cracking vessels, naval guns, armor plate, and many others of an allied nature. Given the detailed drawing of such a part, the first considerations are the size and dimensions of the ingot from which it is to be made. It is obvious that, if the finished forging is to possess the physical properties expected of all press forgings, the dimensions of the ingot must be such that sufficient work may be done upon all parts of it in producing the finished forging so that the grain will be refined and a typical forged structure produced. It is gen-

erally the case that the ingot will be made sufficiently oversize in cross section and shorter in length so that reducing the cross section the desired amount will increase the length the required value and hot-work the steel enough to produce a uniform and fine grain from center to edge. This rather ideal state of affairs is perhaps not always attainable in practice but is the one desired at any rate. In some cases where the best properties are desired, the ingot is stood on end under the ram and its length decreased and its cross-sectional area increased by a method known as *upsetting*—to be described more fully later—and the correct dimensions of the blank obtained in that way as well as some very beneficial work done on the internal structure. The exact amount of working necessary to produce a good forged structure and close all blowholes and porosity depends upon so many factors that the subject cannot be treated here. For ordinary work the largest cross-sectional area of the finished part should be no more than two-thirds of the cross section of the ingot. It should be smaller when high stresses are to be withstood by the part when in service. The exception to this statement is when upsetting is used to increase the cross section of the ingot. The determination of the ingot size requires wide knowledge and experience with the type of steel being forged and the capabilities of the press used.

The analysis of the steel to be used for the part is sometimes decided upon by the customer and sometimes left to the discretion of the manufacturer. In the latter case, the shop superintendent or metallurgist has another factor to contend with as he must choose an analysis which, coupled with the mechanical work done upon it and any necessary heat-treatment, develops the specified minimum physical properties at a minimum cost both as to cost of steel and cost of fabrication. The financial loss is of considerable importance even to the largest companies if a large finished forging fails to meet the specifications for any reason and no profit is made if the cost of production is too high. Heavy forgings, almost without exception, are made of carefully refined, thoroughly deoxidized clean steel and very carefully cast in a type of mold designed to reduce ingot defects to a minimum. Bottom-cast practice is often used. These precautions are desirable and, in most cases, necessary as production costs are high and the added cost introduced by careful steel-

making and ingot practice is negligible compared with the loss involved if the steel is of inferior quality for the purpose for which it is intended.

The general precautions necessary in heating steel for forging have already been discussed and the difficulties involved have been described. For a plant producing forgings of different sizes from ingots of various sizes and compositions, a group of batch-type, oil- or gas-fired regenerative furnaces are better suited to the operating conditions than a continuous furnace. It is advisable, if possible, to forge an ingot without cooling it to room temperature, *i.e.*, the solidified and stripped ingot should be charged into the batch furnace immediately, soaked at the forging temperature, and forged. A partly completed forging should be reheated immediately to avoid the loss of heat contained in it as well as the dangers of cracking. If an ingot has to have a hole bored longitudinally through the center (called trepanning), it must be slowly cooled, usually in ashes or other non-conducting packing. It is then trepanned, preheated to about 1200°F. in a low temperature furnace, transferred to the high temperature or forging furnace, and slowly raised to the forging temperature. The cost of reheating, the time consumed, and the danger of rupturing the ingot are all disadvantages standing in the way of cooling the ingot to atmospheric temperature unless it is necessary. In heavy forging work, then, the batch-type furnace is used primarily to give wash heats to partly forged ingots of various sizes and to soak ingots at the forging temperature, a service for which it is well suited. Care should be taken to minimize scaling at all times.

One of the most difficult problems in making forgings is that of handling. During the forging operation, the upper die is directly over the piece being forged, thus complicating the method of handling. Three general methods can be used. Two cranes are sometimes provided, one on each side of the press, and each end of the ingot is supported from a chain sling by a crane. The chains run over power sprockets at the top so that by moving the chains the ingot may be rotated. The difficulty of this method is that the two crane operators must work in absolute unison at all times, which is obviously a rather difficult feat. This method is used when very heavy ingots are being handled, or ones so short that a single hoist at the center of gravity of the

ingot does not leave enough length on either side of the chain to be presented to the forging dies.

When the ingot is of sufficient length, probably the best method is to balance it on a single hoist and forge down one end to a circular cross section. A long tube is then coupled on to this circular end with clamps. The free end of the tube, which is known as a *porter bar*, is loaded with weights so that the center of gravity of the assembly lies somewhere on the porter bar. The piece can then be handled comparatively easily, and almost the entire ingot presented to the dies at the press. In addition, the entire piece may be charged into the furnace by the crane, a procedure not possible if two cranes (one at each end of the piece) were used. This method of handling works better the tighter the connection between the porter bar and the piece, because if much sagging occurs at the joint, difficulty is encountered in rotating the assembly by means of the chain. In case the ingot has to be supported by a crane on either side of the press, the center is forged down and elongated first so that from this point on, a single chain around this center portion will balance the piece and allow either end to be held between the forging dies, one end of the forging thus acting as a counterbalance for the other. In such a case, only one-half of the piece can be reheated at one time as the crane is able to charge only half of the piece into the furnace. After one end is reheated and forged, the piece is turned end for end and the other end reheated and forged in its turn. By either of these methods, the piece being handled by the crane is guided by one or more of the crew who either are stationed at the counterbalanced end of the porter bar or at the end of heavy tongs clamped to the free end of the forging. Stumpy ingots which cannot be charged for soaking by a crane and to which a porter bar cannot be connected are sometimes placed on a car which can be run entirely into the furnace. In other plants, an electrically operated charging machine is used, the charging device of which is shaped like a huge fork. The ingot is placed upon this fork and the peel pushes the ingot into the furnace and deposits it upon the bottom.

A third method of handling forgings, and one that is widely used on the smaller sizes of press forgings and particularly upon medium sized shafts and circular shapes, is the electric manipula-

tor, one type of which is shown in Fig. 1-XVI. The manipulator runs on a track in front of the reheating furnace and the press is stationed at one end of the track. The peel or arm is capable of revolution as well as forward and backward movement, while the upper portion of the carriage revolves on the base. By this machine, circular shapes may be held on the lower die and turned over at intervals, as well as charged and withdrawn from the furnaces. When handling lengths, a pair of tongs are used to grip the end of the piece.

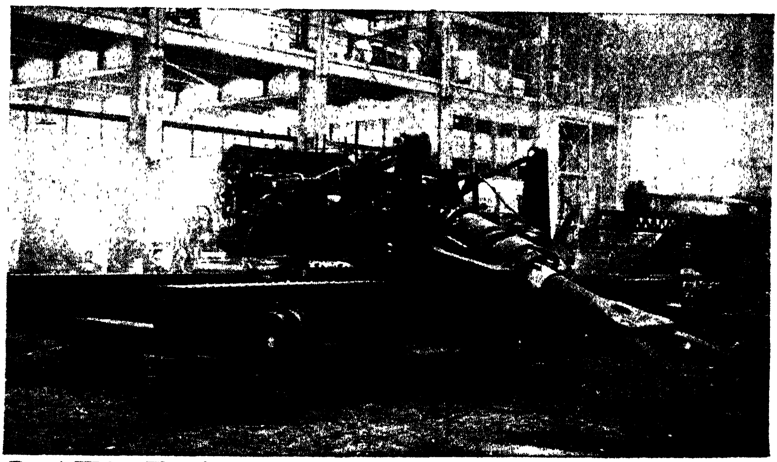


FIG. 1-XVI.—Electric manipulator designed for handling wheel blanks. (*Courtesy of Wellman Engineering Company.*)

Economical forging requires careful planning. The press or presses should be kept in nearly continuous operation and the heating furnaces should not be left empty any longer than absolutely necessary unless they are to be shut down for repairs. Running a heating furnace without any steel in it is a costly waste of fuel, yet if it is shut down and reheated when next needed, the refractories usually suffer from the contraction and expansion. This means that the time necessary to forge each article must be determined fairly accurately in advance, as well as the time necessary for soaking the ingot and the several reheating periods. Furthermore, in order to bring the ingots to the soaking furnaces as soon as they are stripped, it is necessary to work out the melting program to conform to the requirements of the forge shop. As nearly one-half of the cost of producing

a forging is sometimes due to heating costs, any delays or empty furnaces cause the costs to be correspondingly higher. For these reasons, a carefully planned melting, casting, and forging program is essential to economical operation and requires good judgment and wide experience on the part of the person who is responsible for this program.

Three main types of forging dies are used for the various forging operations, while many special dies are designed for particular jobs. The dies come in pairs, one of which is connected to the foundation of the press and the other to the crosshead of the ram. The three common types are known as flat, vee, and swage dies. The dies may be made of carbon steel containing from about 0.50 to 0.80 per cent carbon or of alloy steel containing small amounts of chromium, nickel, molybdenum, vanadium, or tungsten. The first three alloying elements are sometimes used together, while the last two are generally used in connection with chromium. The dies are carefully forged and then given some type of heat-treatment to develop hardness, toughness, and wear resistance.

Flat dies are used principally for square or rectangular forgings. They should be longer than the width of the work to be made, while the breadth of the die face is usually dependent upon the power of the press. Very narrow dies are used, however, to forge out short necks between projections on the forging. In flat dies, the edges and portions of the face close to them are the main working parts, the remainder of the face having principally a straightening action on the work. When using flat dies, it is the usual practice to keep the forging square or rectangular in cross section until it is down to the desired size on two sides while any part of the forging that is to be round is then made octagonal by pressing the corners and finally rounded by pressing down the smaller corners.

In producing long forgings, it is the common practice to pass the forging through the press from one side to the other and then turn it before feeding it back again. It is much faster to move the forging along after each squeeze of the press than to turn it, because the crane can be moved ahead slightly while the press is squeezing a certain area. When the pressure is released, the piece shifts almost instantly to a new position for the next stroke of the ram. In making intricate forgings, flat

dies are necessary as many special operations have to be made with their aid by interposing special tools between the upper die and the work. These special tools are usually on the end of long bars and are placed by hand or by a crane if too heavy to lift and control by hand. As an example of this type of operation, a slicing bar is used to cut deeply into the piece being forged or to cut it in two. The tool consists of a small steel plate fastened to the end of a long rod, and it is held on edge on top of the work while the flat upper die comes down and forces the plate into the forging.

Vee dies are often used in making round forgings. The upper one is flat while the bottom die is V shaped in cross section and the work rests in this trough during the forging operation. The bottom die is sometimes made in one piece with a V-shaped aperture cut in the large block but, as the sides wear away rapidly, it is usually better to make the die out of a flat lower piece and two triangularly shaped parts held together with a holder. When pressure is applied, there is a three-point contact between the work and the dies and deformation takes place at three places on the periphery of the work at each stroke of the press. It is the usual procedure to rotate the piece after each squeeze until a portion of the forging equal in length to the width of the faces of the dies is reduced in size by a definite amount. The piece is then moved enough to bring a new section of the forging under the dies. These dies are quite convenient for producing a short round forging with a large number of different diameters or if special tools are to be used in producing the forging. The production of long round forgings is a slow process by this method, however, as the flat places produced by the squeezing must be blended into a round and this necessitates many applications of pressure and much rotation of the part. This method is able to keep the scale cracked off the surface of the piece and produces a well-finished surface on the completed forging.

Swage dies are also used in the production of round forgings. Curved grooves are cut in both the upper and the lower dies and must be carefully designed in order to give satisfactory results. As with flat dies, the piece is passed through the press without turning when long lengths are being forged and turned only when the piece is started back through the press. Long shafts of constant diameter can be produced faster between these dies than

between vee dies, other things being equal. A disadvantage of this type of die is that a given size can be used on only a limited range of sizes of forgings and in passing from a large size to one considerably smaller, changes in the dies have to be made.

Having covered the main types of dies used and the methods of handling the material, the various forging methods can now be taken up. As the ingot is brought to the press, it has a very coarse, columnar grain condition and some porosity in the central portion. Both these defects cause the ingot to be tender and the first forging operation consists of working the ingot as completely as possible over its entire longitudinal surface to refine the grain and break up the columnar dendritic structure in the outer layer. The kneading action of the press should extend to the core in order to refine the grain and compress the porous portions into a homogeneous mass. This operation results in a decrease in cross-sectional area and an increase in length. If two or more forgings are to be made from the ingot, it can now be cut into lengths by the use of the slicing bar. From here on, the forging procedure depends entirely upon the forging being made so the discussion will be limited to a description of the more common types of general operations carried out on forgings.

When forging is done with the distinct aim in view of decreasing the cross-sectional area and increasing the length of the piece, the procedure is known as *drawing* and can be accomplished by the use of any of the types of dies described above. In ordinary operations, the axial length of the forging is parallel to the axis of the original ingot. When it is desired to increase the width of the forging without appreciably increasing the length, flat dies are used and the operation is known as *spreading*. In this case, however, the long direction of the die face is parallel to the long axis of the forging rather than at right angles to it. This causes the metal to spread sideways rather than lengthwise as in drawing.

When a forging is *upset*, the axial length of the whole forging, or a part of it, is decreased while the cross-sectional area is increased. If the entire ingot is upset, a short thick piece can be produced from a comparatively small ingot, whereas if it were produced by drawing, an ingot of much larger cross section would have to be used. Using the larger ingot would cause some of the length to be left over while the larger ingot necessarily has a

larger area of axial segregation. By using the upsetting method, an ingot can generally be used which is of just about the right weight to produce the finished forging when proper allowance is made for crop ends and waste. The limitation in this regard is that if the length exceeds the diameter by too great an amount, the piece is apt to buckle during the upsetting operation. Upsetting is an excellent method of breaking up a segregated structure, when carefully conducted in conjunction with or followed by drawing, and usually results in a forging of excellent structure and properties.

Upsetting is also often used in producing flanges at or near the ends of forgings, particularly in marine shafting. In such cases, the ingot is forged down into a shaft of the proper size and cropped. A small portion of the shaft at the end is then heated and this portion then upset into a flange, the portion of the shaft nearest the flange being held in dies of suitable diameter. These shafts are usually longer than the lift of the ordinary forging press and a horizontal press must then be used. Other applications of upsetting are in making turbine disks, wheels, etc.

The production of hollow forgings is a different proposition in some respects from the ordinary types of forgings. Hollow forgings are required for naval guns, wheels, boiler drums, oil cracking stills, etc., where the service is too severe for welded material. Such heavy parts cannot be pierced in the way seamless pipe is handled but must be trepanned (trephined) or punched. If the hole is to be bored or trepanned, the piece is very slowly cooled and a hole is drilled through the center of the material in a longitudinal direction, thus removing the area of greatest segregation and possible weakness. The hole is rarely drilled as large as the final desired size because it is cheaper to forge the hole larger than to drill it to such a large size. The piece is carefully reheated to the forging temperature and a mandrel bar inserted in the hole. This bar also acts as a porter bar to handle the forging and, if small in diameter, is usually water cooled. The piece is supported under the upper die of the press by placing the mandrel on two supports, one on either side of the press, and the central cavity is enlarged by a process known as *expanding*. The upper die is flat with its long direction parallel to the mandrel and is situated directly above the mandrel. The pressure is applied by the upper die to the metal between the

mandrel and the die, in this way spreading the metal sideways with very little increase in length. The mandrel is rotated slightly after every squeeze, thus enlarging the diameter of the piece and decreasing its wall thickness. If no increase in length is necessary to produce the finished forging, the above operation is a finishing one, but usually some drawing is required. In the latter case, the mandrel is withdrawn when the central cavity has been expanded to an internal diameter slightly larger than the desired finishing diameter. A mandrel of the same diameter as the inside finishing diameter is then inserted and the forging lengthened and decreased in outside diameter as well as wall thickness by forging between either vee or swage dies in the usual manner. The mandrel bar is tapered slightly to aid its withdrawal but hydraulic extractors are often necessary to remove it from the forging. It is considerably longer than the forging and serves as a porter bar when the piece is turned or moved. Vee dies by bearing only at three points cause the metal to fit more loosely to the mandrel than do swage dies that bear nearly all around. Care should be taken to prevent the metal from sagging away from the mandrel in that portion which is not between the dies. If this occurs, the internal diameter will not be uniform.

Owing to the expense and difficulties involved in cooling large pieces for trepanning and then reheating them, they are often either punched or cored while hot. In comparatively small work, such as wheel rims, where the thickness through which a punch must be forced is not too great, punching is the common method. The punch is a tapered cylinder with a slightly rounded flat nose. This punch is forced part way through, the piece turned over, and the hole finished by using a larger punch. By this method no metal is removed, but it is expanded away from the center by the punch. The hole can subsequently be enlarged by the method described above. In heavier work, a tubular punch is sometimes used and by this means the core of the piece is removed as it remains inside the punch. This method has the advantage of removing the segregated core from the forging.

High-pressure boiler drums, oil cracking units, and like pieces of equipment often require closed or bottled ends (the end of the tube is shaped like a bottleneck and with a small hole). The closing operation can be done as the last forging operation if only one end is to be closed and any necessary internal machining

done from the open end. If both ends are to be closed and machining is necessary, the forging must be slowly cooled, machined inside, and the ends reheated and forged shut, or nearly so. Swage tools are used but they are specially designed to shape the ends to the required size and contour. At each squeeze of the press, the end is made elliptical in shape while the portion of the periphery not in contact with the dies is increased in wall thickness by the squeezing action. The tube is rotated at each squeeze to repeat the thickening action all around the circumference so that the hole is ultimately closed down while the walls are thickened. The dies unavoidably draw out the metal at the ends to a small degree, thus producing a neck. If flat or dome-shaped ends are desired, the ends are flattened by appropriately shaped dies in a horizontal press.

The finishing operations on the forgings vary widely with the use for which the part is intended. Most forgings require machining, massive lathes, shapers, etc., being provided for this work. Also, most forgings are given some type of heat-treatment, ranging from a simple annealing treatment to a complex quenching and tempering cycle. The purpose of such treatments is to relieve internal strains and produce the desired physical properties and grain size in the forging. Complicated quenching and tempering operations are dangerous with very large forgings because of the dangers of cracking during and after quenching. The necessity for annealing most large forgings lies in the fact that the power required to work the piece at or close to the critical temperature is quite large while the large size makes for slow cooling. Both these factors result in a fairly large grain size in the finished forging and the only way to replace it with a smaller grain size is by annealing. In some cases and particularly when the finishing temperature is high, two annealing treatments in succession are given the piece. Large forgings are not allowed to cool all the way to atmospheric temperature until the last annealing treatment has been made. Even then the cooling must be carefully watched to prevent cracking.

Hammer Forgings.—The double-acting steam hammer is perhaps better suited to the production of forgings of moderate size than is the forging press because, in the range where it can work the metal through and through, it is a faster means of reduction than the press. The methods used in forging are

very much like those used in connection with the forging press and only the variations from the methods already described will be mentioned here. Large ingots are rarely forged down under hammers as it is much cheaper to roll the ingots to blooms, cut them into the desired lengths, and reheat for hammer forging. For high-quality work it is often necessary to pickle the blooms or billets before reheating for forging in order to bring out any surface defects so that they may be chipped out. A pickling

FIG. 2-XVI.—Pickling machine designed for pickling billets. The central vertical support moves up and down, thus agitating the material in the solutions. (*Courtesy of The Mesta Machine Co.*)

machine designed for such work is shown in Fig. 2-XVI. This same type of pickling machine is used for pickling many other classes of work and has been referred to in Chap. XII.

The same main types of dies are used as have been already described, except that vee dies sometimes consist of both V-shaped upper and lower dies. Tools similar to those used by a blacksmith are applied to steam hammer work, except that they are larger. Heading tools and bolster blocks are used to forge upset ends on shafts. Steel blocks of rectangular section, used as gauges when bringing a forging down to size, are held under the hammer on long rods. Owing to the shock in the process, forg-

ings are somewhat difficult to handle under the hammer. Forgings that are too heavy to be handled by tongs in the hands of a workman are carried by large tongs supported by a chain while a workman guides the forging during the operations. Large forgings can be handled by a porter bar or by a manipulator. Flat dies are generally used for making shafting or bars under the hammer. Here the reduction of the original piece usually takes the bar to the form of a hexagon or octagon. The piece is subsequently rounded up by either knocking off the corners with light blows between flat dies or by using swage dies.

At one plant, rims for locomotive wheels are hammer-forged from individual ingots, each one containing just the right amount of metal to form a rim of the desired size. The small ingot is in the general shape of a chocolate drop and is known by that name. After reheating, the ingot is forged down under the hammer to a pancake shape, being handled by a traveling electric manipulator. A punch is then supported over the center of the forging and driven almost through by blows of the upper die. The forging is turned over and the rest of the hole punched, after which the forging is flattened by one heavy blow and removed for reheating. The reheated rim is taken to another hammer where it is hung over a round projection (called a horn) which sticks out of the side of a specially shaped anvil. The rim is expanded in this way by forging the metal out sideways between the hammer head and the horn, the rim being turned slightly after each blow. The expanded rim is reheated and then rolled in a special machine which expands it to the final size, rolls the flange, and trues up the piece in general. After cooling, the rim is machined to exact size. The method has the advantage of having almost no waste of metal anywhere in the process.

The steam hammer is particularly suited to the forging of high carbon tool steels and high alloy steels, including the several varieties of stainless steels. The reasons for this are that such forgings are almost always of moderate or small size and the force and rapidity of the blows of the hammer are under excellent control at all times. These steels, owing to their greater stiffness at forging temperatures, require about 25 per cent more blows than ordinary steels (other things being equal) and the dies do not last as long owing to the greater hardness of the material. In addition, stainless steels and other high alloy steels have much

narrower ranges of forging temperature than carbon steels and more frequent reheating is necessary.

Drop Forgings.—Drop forgings form a very important group in the general forging field when considered from the standpoint of value of product as a very wide variety of articles are produced by this method. Two main types of hammers are in use: steam-actuated drop hammers and board drop hammers. In the latter type, the lower end of a maple board is fastened to the upper portion of the ram. The upper end of the board travels between two rolls which are belt driven and revolve in opposite directions. An automatic mechanism causes the rolls alternately to squeeze the board and lift it by their revolution and then spread apart, allowing the board and hammer to fall. Sometimes, air cylinders are used in place of steam cylinders to operate drop hammers as there are advantages in favor of compressed air in small plants. The practical limit of board drop hammers is about 2,500 lb. while steam drop hammers are made up of several tons in size, the basis being the weight of the falling parts (ram and hammer head).

A somewhat analogous type of forging hammer is the trip hammer, which consists of a heavy hammer head and arm which is pivoted and operates through an arc. This machine is, in reality, merely a mechanical sledge hammer, but the rapidity of the blows can be closely controlled and changed very rapidly. They are seldom built larger than a few hundred pounds and are equipped with simple dies for the production of such articles as chisels, picks, axes, and hoes.

Probably the most serious problem in the production of drop forgings lies in the design and manufacture of the dies. The design of the die depends upon the size and shape of the forged piece as well as upon the steel being forged. In the general case, however, one-half of the impression is cut in each die so that when the two are placed together face to face, the cavity is the desired size and shape of the finished part, proper allowances being made for shrinkage during cooling. There are definite limitations, however, upon the shape of pieces that can be drop-forged. For example, the depression cut in the die cannot have vertical sides but must taper somewhat or the cavity cannot be filled nor can the forged piece be withdrawn. Also, any hole or depression in the forged part must have its sides parallel with

the direction of travel of the upper die and reentrant angles must be avoided.

Some drop-forging dies are made of carbon steel (0.60 to 0.65 per cent carbon) but are usually used only when a limited number of forgings are to be made as this cheaper and less wear-resistant die will stand only a very limited amount of service. When high-production dies are needed or those which will stand high working temperature (1000°F.), alloy steel dies are always used. Nickel-chromium steels with or without a little molybdenum content are the ones generally employed. These are hardened by heat-treatment. In some cases, it is advantageous to make the body of the die of a cheap material and face it with a high-grade alloy steel. It used to be that the dies had to be cut and then heat-treated, a procedure that resulted in much loss because of the warping of the dies during heat-treatment or the cracking of intricately shaped depressions. At the present time, sufficiently good cutting methods are at hand to allow the cutting of most dies after they are hardened, thus minimizing the losses. The surfaces of the impressions of some dies are being chromium-plated at the present time. A layer of about 0.003 in. produces a very hard and wear-resistant die. Nitrided dies are used to a limited extent where die temperatures up to 1000°F. are encountered.

The cutting of the depressions in the die faces is entrusted only to highly skilled diemakers and a large part of the cost of the die lies in their wages. When hardened die blocks are being cut, machine cutters of high-speed steel operating at fairly high speeds are used to rough out the depressions and the remainder is either ground out or chipped out with small air-driven chipping hammers. The depressions are then burnished with horsehide polishing wheels, a hard abrasive being used for the rough polish and rouge (Fe_2O_3) for the final polish. Dies carefully made in this way will produce drop forgings that require machining only on the finest fitting surfaces.

Two or three different depressions are usually cut in the dies, corresponding to the stages of the formation of the part. The first is called the *rough blanker*, the second the *blanker*, and the third the *finisher*. The rough blanker and the blanker do most of the work, the finisher only setting the final shape; consequently it does not wear out rapidly. If the production is

limited, the rough blanking impression is omitted. A small gate is left at one end of the impression so that the piece will not be cut off the bar by the die.

On small drop forgings, the operation is about as follows: The ends of several bars are heated in a furnace and are withdrawn in succession for forging. The end of a bar is first inserted in a small depression at one corner of the die, known as the *fuller* or *swager*, where a piece of metal of the correct size is separated from the bar by several blows of the hammer except for a thin connecting strip to serve as a convenient handle. The metal on the end is roughly shaped in a small depression at another corner of the die, called the *edger* or *roller*, and then rough-blanked in the first of the three main die depressions. After the piece has conformed to that impression, it is moved to the blocker, which gives the forging its general shape, and then to the finishing impression. After these operations, which may take many blows for each one, the piece is cut from the bar and the bar replaced in the furnace for heating. A jet of compressed air is directed on the lower die during the forging process to blow out any scale that may collect on the lower depression.

The foregoing procedure causes metal to flow out between the die faces, forming a fin or flash around the forging. Also, any holes inside the forging are not completely cut through as a thin film of metal still covers the hole. The cooled piece is put over an outside trimming die which has a hole through it of the exact outline of the finished part. A sharp blow from a punch pushes the piece through the trimmer, thus shearing off the fins. Another punch, called an *inside punch*, opens any holes in the forging that were not cleaned out. The piece must be trimmed hot if the steel is too hard to be trimmed after cooling and, after hot trimming, the piece is restruck in the finishing impression. High carbon and alloy steels are always hot-trimmed.

Shrinkage of the forging on cooling is hard to estimate accurately in some cases and small drop forgings cannot be made extremely accurate except by a process known as *coining*. The cold, trimmed piece is placed between dies that are very accurately cut to size and struck several blows with the upper die to make it conform to the die impression. Very powerful machinery is necessary for this operation and presses are sometimes used instead of hammers. In fact, within recent years many parts

formerly made under a drop hammer are being forged between the dies of a hydraulic press in exactly the same manner. The press has the advantage of being able to extrude metal into more intricate shapes than the drop hammer and fewer steps are necessary.

In large production work, automatic machines, known as *heading* machines, are frequently used to blank out parts from bar stock by upsetting the end of the bar with a horizontal ram and cutting off the upset portion. Such a process is particularly applicable to forging blanks for ring gears, the blank being subsequently reheated and forged to final size under the drop hammer. The upsetting produces an excellent forged structure in the metal and is often used when high strength is desired of the finished part.

Suggested Questions for Study and Class Discussion

1. Describe how you would forge, under a large hydraulic press, a 20-in. diameter by 7 ft. long octagonal ingot to a round section 8 in. in diameter, which must have excellent physical properties.

2. Describe the methods used in making hollow forgings under the hydraulic press.

3. What is upsetting? What are its advantages?

4. Describe the methods of making drop forgings. Why are the dies of such great importance in this work?

5. What are the advantages and disadvantages of drop forgings over castings?

CHAPTER XVII

THE STEEL FOUNDRY

The function of the steel foundry is to produce steel shapes by casting them in molds made principally of sand but sometimes of other materials. Steel shapes that are too intricate to be made by rolling or forging must be cast. Large, comparatively simple shapes, which are desired for their bulk and weight rather than for outstanding physical properties, are often cast rather than forged because of the greater cost of the latter method in such cases. Also, if only one or a few parts are to be made, it is often cheaper to cast them than to set up the machinery for rolling them or to make the dies for forging them. The question of physical properties is most often the deciding factor.

Steel foundries may be roughly divided into three classes. The first, the tonnage foundry, makes a great number of castings from relatively few patterns and generally of shapes that can be made only by casting. The tonnage foundry attempts to obtain long-term contracts for supplying these shapes and frequently agrees to furnish them at a flat price per pound of metal. By this standardization, the problems of such a foundry may be reduced to that of a rolling mill and the plant attempts to turn out a maximum number of castings per day as the profit on each casting is generally very small. The mass production of a limited number of shapes permits the use of laborsaving devices and conveyers while the workmen, because of constant repetition, are able to work at maximum efficiency.

The second class is the jobbing foundry, a very descriptive name because this type of foundry takes any kind of job that comes along that it is equipped to handle. The problems are quite different in a jobbing foundry as each casting is a complete problem in itself. The design and construction of the mold must be correct the first time it is tried or the cost of recasting the part will seriously decrease the profit made on the article. Some allowance for this is always made in figuring the cost of

the job but unforeseen difficulties often destroy the value of such advance calculations. The person in charge of a jobbing foundry must be a man of excellent judgment and wide experience if he is to succeed.

The specialty foundry makes up the third general class and is so called because it makes a specialty of some alloy steel of particular excellence for certain purposes, or of some class of difficult castings especially suited to a particular steelmaking process and hard to make by any other. The output of such foundries is small and the profit per pound is large if correctly operated. This type of foundry may make all shapes in its steel specialty, in which case its problems are partly those of a jobbing foundry. On the other hand, it may specialize in intricate shapes, in which case it tends toward the tonnage foundry in that it makes a large number of castings of special shapes for a few applications. The classification of foundries given here overlaps to a considerable extent but it does give the student an idea of the variety of problems arising in the foundry industry.

All the commercial methods of making or melting steel are used in the foundry industry in the production of molten steel for castings. The choice of a method of steelmaking for a given foundry or a given type of work depends upon so many factors that a detailed discussion cannot be attempted here. In general, plain carbon steels are made by the Bessemer process (side blown and bottom blown), the acid and basic open-hearth processes, and the acid and basic electric processes. Alloy steels are made by the acid and basic electric processes, in the high-frequency induction furnace, and, to a limited extent, in the rocking arc furnace. The pig and scrap process is the only one used in foundry work in connection with the open-hearth processes, while in all of them, with the exception of the Bessemer process, scrap heats are made to a considerable extent. Superrefining open-hearth steel in the basic electric furnace, as well as duplexing the Bessemer product in the basic open hearth, is used in tonnage foundries.

One of the important factors to consider in choosing a steelmaking method is that of whether the furnace operation is to be steady or intermittent. The open-hearth processes are best suited to steady operation as the cost of intermittent operation is very high because the furnaces must be kept hot. Electric

furnaces are much better suited to intermittent operation because they are smaller and do not employ regenerative systems. The Bessemer process is best suited in most cases for intermittent operation on plain carbon steels while the induction furnace is probably best suited to the intermittent production of alloy steels. It is a fact, though, that the cost of steelmaking by all processes is less if the operation is steady.

In the opinion of John Howe Hall, one of the country's foremost foundry metallurgists, the choice of a steelmaking method,

TABLE 1-XVII.—RATING OF FOUNDRY STEELMAKING METHODS

Process	Quality, (1) best	Flexibility, (1) most flexible	Suitability for small work, (1) most suitable	Cost of steel, (1) lowest	Tonnage, (1) highest	Cost of installation, (1) lowest	Cost of installation per ton, (1) lowest
Crucible	3	1	1	7	6	1	7
Basic electric	1	2	2	6	5	3	6
Acid electric	2	2	2	3	4	3	3
Acid open-hearth	4	4	5	2	1	5	4
Basic open-hearth	5	4	6	1	1	5	5
Side-blown Bessemer	6	3	3	4	3	2	2
Bottom-blown Bessemer	7	3	4	5	2	4	1

Note: Electric furnace refining basic open-hearth steel stands between No. 4 and No. 5 in cost of steel.

Gas-fired crucible furnace stands between No. 3 and No. 4 in cost of installation.

Electric furnace refining hot metal stands between No. 1 and No. 2 in cost of installation per ton.

in the light of the most important factors affecting it, is as given in Table 1-XVII. Although he may have changed his mind in regard to some details since it was published in 1922, the classification is still correct in a general way. The crucible process is a matter of historical interest only, because, as far as the author is aware, no plants are in operation in this country at present. The high-frequency induction furnace has taken the place of the crucible process for foundry work. By quality is meant the quality of the steel produced by the best practice

possible with each method. It is obvious that any of the processes can produce steel of poor quality and the above classification is based on careful and intelligent operation. Flexibility means the adaptability of a steelmaking method to the production of widely different analyses, while suitability refers to the ease with which small and intricate castings can be poured from the product of the steelmaking method. The rating under "cost of steel" is based upon estimates including a large number of factors including cost of raw materials, cost of conversion into steel, time of operation, etc., and varies from time to time as all the factors affecting it fluctuate. By tonnage is meant the possible production of one unit of average size of each type and affects the number of units installed in the foundry more than the choice of the method. After a little thought, it will become apparent that the ratings given the various processes in the table do not hold rigorously because too many variables enter in. In a general way, however, it presents a picture of average conditions for foundry work. The reasons for the ratings given will become apparent in the following discussions of the various steelmaking processes as applied to foundry work.

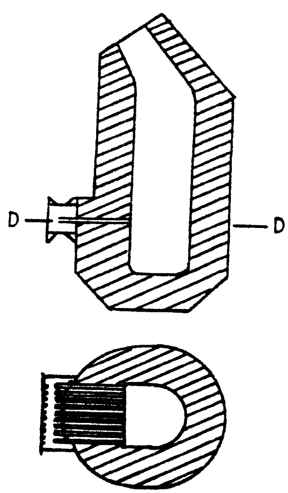


FIG. 1-XVII.—Section drawings of a Stoughton-type side-blown converter. (*After Stoughton.*)

The Bessemer Process.—In foundry work, small bottom-blown converters are used to some extent, a vessel of 3-ton capacity being typical. The construction and operation of the small converter are practically identical with those of the larger ones used in ingot production and will not be considered further here. Most converters used in steel foundries, however, are of the side-blown eccentric type. Two general types of side-blown vessels are in use: the Tropenas and the two-piece vessel of which the Stoughton design is typical (Fig. 1-XVII). The main feature of both of these types is that the blast is introduced through tuyères placed part way up one side of the shell so that the blast is directed at the surface of the bath and not blown through it.

The Tropenas converter is built in one piece with a hinged bottom much like that used on a cupola. Since the tuyères wear away more rapidly than any other portion of the lining, the lining is thicker on this side. In spite of this, some patching is necessary after every heat and the tuyères must be replaced after about 20 or 30 heats. In the two-piece type the lower portion of the vessel, consisting of the tuyères and bottom, is removable for repairs. In the Stoughton design, the tuyères are of steel pipe set in the lining and last considerably longer than brick ones. The vessel is also higher and narrower than the Tropenas type, thus minimizing splashing.

The operation of side-blown converters differs from that of bottom-blown vessels only in details. Molten metal is necessary and, unless the foundry is an integral part of a large plant that can furnish molten pig iron of Bessemer grade direct from a blast furnace or mixer, cupolas must be employed to provide molten pig iron. With the converter on its side, the proper amount of molten pig iron (1.75 to 2.0 per cent silicon and 0.30 to 0.50 per cent manganese) is poured in. The amount poured in is such that when the vessel is tilted up to within 5 to 10 deg. of the vertical, the surface of the metal comes just to the bottom edge of the tuyères. The blast is turned on and the air strikes the surface of the bath across its entire width. The reactions taking place are the same as in bottom-blown practice but the manner in which they take place is somewhat different. Instead of FeO being formed at the bottom of the bath and imparting its oxygen to the impurities during its travel upward through the bath (bottom-blown vessel), the FeO forms at the surface and the elimination of the impurities takes place mainly by reaction between FeO in the slag and the metal underneath. The operation is somewhat slower, therefore, and takes anywhere from 15 to 30 min. for a 3-ton heat. The removal of silicon and manganese is slow and somewhat intermittent, and some carbon is oxidized in the early period, but as soon as the carbon starts to be oxidized rapidly, a long, white feathery flame pours from the mouth of the vessel. During the early part of the blow, the carbon monoxide formed burns to CO_2, resulting in hotter metal than is obtained from bottom-blown vessels. When the carbon is nearly all burned out, the flame drops in the characteristic manner and the vessel is turned down. It is usual in foundry

practice to turn the vessel down when the carbon is in the neighborhood of 0.20 per cent, rather than wait until a complete drop in the flame occurs because of the dangers of overoxidation with this method. Deoxidation and recarburization are usually carried out in the converters in side-blown practice and molten reagents are generally used. The hot metal is poured into a large ladle and taken to the molds where it is poured. The metal is often transferred to shank ladles for pouring small castings.

The side-blown vessel has several advantages over the bottom-blown type for foundry work which have caused its widespread popularity in this country. In the first place the amount of blast is much less. In fact, a little over 1-lb. pressure is all that is needed in the latter stages of the process. This state of affairs greatly decreases the amount of auxiliary equipment needed to furnish the blast and is an important consideration in small plants. In bottom-blown types, enough pressure is needed at all times to keep the metal out of the tuyères. Furthermore, the side-blown converter is seemingly much less apt to turn out wild or overoxidized heats. This may be because the metal is less charged with gases by virtue of the fact that the blast is blown over the surface of the metal rather than through it. For the same composition of the charge, side-blown metal finishes hotter than bottom-blown metal because much of the heat of the oxidation of CO to CO_2 serves to heat the metal. Castings must be poured hotter than ingots and, for that reason, the side-blown converter is often preferred. Repair of the lining and upkeep in general are also somewhat less with side-blown types while greater ease of repair is another important factor.

The Bessemer process in foundry work is used mostly in making the cheaper grades of carbon steel castings and the process is usually intermittent in operation unless a large number of converters are used. Each vessel is usually run only every other day, the alternate days being devoted to repairs and to heating the vessel for the next campaign. Castings of Bessemer steel must generally be lower in phosphorus and sulfur than Bessemer steel that is subsequently rolled, because the fabricated parts have the advantage of hot working while the attempt is made to cut the impurities in Bessemer castings to a minimum in order to make them as strong as possible. This fact requires

that carefully selected pig iron be used, which serves to increase the cost of the process. Furthermore, the metal loss through oxidation is high. In general, it may be said that the Bessemer process has the same advantages and disadvantages for foundry work that it has in ingot production except that intermittent operation and low first cost are often greater advantages in foundry work. The Bessemer process is used to some extent in the production of alloy steel castings, in which field it seems to be best suited to the making of manganese steel castings. Molten ferroalloys must be used and a further disadvantage is that alloy scrap cannot be used economically in the process.

The Open-hearth Processes.—Both the acid and basic open-hearth processes are conducted in exactly the same manner as in ingot production, which has already been considered. Smaller furnaces are used for foundry work, however, because it would take a large mold department indeed to keep up with the production of the large modern open-hearth furnaces. The maximum size is about 50 tons capacity while the minimum is about 15 tons. Smaller sizes than this have been operated but are not economical because the cost of operation becomes too high in proportion to the output. Owing to the fact that casting temperatures are high, heats must be tapped hotter than in ingot production, causing the life of the furnace to be shorter and the upkeep higher. Oil firing is very popular for foundry open-hearth furnaces.

Previous to the last few years, acid open-hearth steel was considered to be superior in quality to basic steel for castings and was always specified for high-grade work in preference to basic open-hearth steel. This was due to the fact that acid steel could be more thoroughly deoxidized and could be made more free from objectionable inclusions than basic steel. On the other hand, acid steel is more expensive because of the greater expense of the raw materials but for high-quality castings the premium is paid because of greater freedom from blowholes, which are especially dangerous in castings because they are not closed by any subsequent treatment. With the recent advances in basic practice, however, it is probable that basic steel can be made equal in quality to acid steel. The acid process is still more "foolproof" and, for that reason, is still generally preferred for high-quality castings. In fact, at least one-half of the

tonnage of acid open-hearth steel goes into castings at the present time.

The open-hearth processes in general are quite flexible in operation as they can be adopted to the production of all carbon steels and alloy steels of low alloy content. The quality of their product is better than that of the Bessemer converter but they possess the rather serious disadvantage of not being well adapted to intermittent operation and the cost of installation is comparatively high. These processes are principally used in large tonnage foundries where their cost of operation is at a minimum and the best operating practice can be put into effect. Enough molds can be made in large shops to take an entire heat, a procedure not usually possible in small shops. In the latter case the necessity of scrapping high-grade metal makes the cost of the process almost prohibitive. In general, it may be said that the open-hearth processes are used in tonnage foundries for making the better grades of carbon steel castings and, to a small extent, low alloy steel castings.

The Electric Furnace Processes.—The bulk of the best quality carbon steel castings and most of the alloy steel castings are made in electric furnaces at present. The basic process has found favor because it is able to produce probably the best quality of steel obtainable and at the same time make it or superrefine it from comparatively inferior grades of raw materials. By proper operation, nonmetallic inclusions, sulfur, and gases may be practically eliminated—factors that are very important when producing high-quality castings. Alloy steels may be made with very little loss of ferroalloys and alloy steel scrap may be melted with very little loss of alloying elements during melting. The process is adaptable to intermittent operation and can easily superheat the metal to any desired degree, and the smaller sizes (3 to 10 tons capacity) are economically operated in foundry work. It should be remembered, however, that the cost of the process is higher than that of the Bessemer and open-hearth processes and electric steel castings can be used only where their advantages of sounder steel offset their higher cost. This reduces its field of use to the production of castings of the best quality of carbon and alloy steels. The operation of the basic electric process has already been described. Except in large

foundries where superrefining is done, the cold melt process is most commonly used.

The acid electric process has come to be one of the most important steelmaking processes for foundry work within recent years. In fact, practically all of the acid electric steel made goes into the production of castings. For that reason, a discussion of the process was deferred until this time. The metallurgy of the process is essentially the same as that of the acid open-hearth process although the manner of carrying out the process is somewhat different. The furnace used is of the Heroult type and is constructed like the ones used in the basic process except that the bottom is of sintered silica sand. As is usual with acid processes, phosphorus and sulfur cannot be eliminated; hence the charge (scrap) must be limited to material that contains 0.04 per cent or less of each of these elements. Most of the charge is made up of foundry scrap with selected scrap from outside sources making up the remainder. In charging the furnace, plate punchings (if available) are charged on the bottom to form a compact mass, the heavy and bulky pieces charged next, and the rest of the scrap charged on top. It is desirable to heap the charge up in a mound with the highest point in the center of the furnace.

During the melting-down stage, some oxidation of the charge cannot be avoided while rust or scale on the scrap forms a considerable portion of the FeO in the slag after melting. If possible, the carbon content of the charge should be about 0.05 per cent higher than the percentage desired in the finished heat but considerable deviations from this rule are unavoidable in many cases. For economical operation, however, the melter should know the approximate average carbon content of the charge before melting. The refining process consists largely in the removal of nonmetallic particles produced in the steel during the operation of melting. These slaggy particles may be produced by the oxidation of silicon, manganese, or other oxidizable elements in the charge or may be present from sand that contaminated the charge.

The refining stage of the process is conducted much as in the acid open-hearth process. During the melting stage, a considerable amount of silicon and manganese and part of the carbon

are oxidized through the agency of FeO, which is formed by the oxidation of iron. The carbon is worked down by adding lumps of carefully selected iron ore at intervals until the carbon content is well below the desired final value. As soon as an open pool of metal has formed under the electrodes, careful additions of iron ore may be made to oxidize the impurities and some limestone is also charged to keep the slag from becoming too high in FeO; since CaO will replace FeO in the slag, the FeO will revert to the metal. The elimination of carbon in the bath is accompanied by a reduction in the amount of FeO in the slag and the former process can be followed by watching the character of the slag and of fractured steel samples from time to time. After the bath has become completely molten and contains sufficient iron oxide to reduce the carbon to the required amount, the rest of the refining stage of the process mainly consists in allowing the nonmetallics time and opportunity to rise out of the bath and enter the slag blanket.

This is probably the most critical stage of the furnace operation as very small oxide particles that have melting points higher than the temperature of the bath are very slow in rising out of the metal. The suspended oxides need time and a proper slag condition for efficient removal. Too often the refining part of the process is carried out so rapidly that the carbon is well down before the oxides formed during the oxidation stage have had time to remove themselves from the bath. When this type of operation is used, the process is one of steel melting and not steelmaking and cannot be condemned too heartily. Also, if the slag becomes too acid in character, it becomes very viscous and fails to pick up effectively the oxides from the bath. As the heat comes to condition, the steel, largely freed of nonmetallics and with its iron oxide content at a minimum, begins to pick up silicon by reduction of the SiO_2 in the slag. The silicon thus produced reacts with FeO dissolved in the metal, forming more suspended particles of SiO_2 which must be removed by the final scavenging additions. It is believed by some investigators that if this reducing action of silicon into the metal is allowed to proceed too far, it causes the sluggish condition of the finished heat which is sometimes met with in acid electric steel. For intricate castings, the steel must be highly fluid and, if it is sluggish, owing to the above effect, it is said to be "overreduced." The effect

can be detected by spoon tests and corrected by the addition of FeO to the bath or slag.

With the carbon at the desired value, the bath freed as completely as possible of nonmetallics, and the reduction of the FeO content by reduced silicon carried to the desired degree, deoxidation of the bath can be started and is always carried out in the furnace. If the furnace operation has been correctly con-

FIG. 2-XVII.—Tapping a 6-ton electric arc furnace. (*Courtesy of Bethlehem Steel Corporation.*)

ducted up to this point, the bath will be boiling very gently, showing that the carbon elimination has about reached a standstill. The best practice is to kill off the boil by adding carbon in the form of a high carbon iron of as low a silicon content as possible. By this practice, it is possible to eliminate most of the FeO in the bath by reaction with carbon, producing a mild boil which aids in stirring the bath and bringing the suspended oxides into contact with the slag blanket. After this has taken place, ferrosilicon and ferromanganese are added together to complete the deoxidation. If the FeO were removed by silicon alone, suspended SiO_2 would result, while by removing most of the FeO

by the carbon in the iron the product of the reaction is gaseous and, therefore, does not increase the nonmetallic content of the bath. Both ferrosilicon and ferromanganese are added to complete the deoxidation because their action is powerful and because their combined reaction with the remainder of the FeO produces fusible manganese silicates which coagulate and remove themselves rapidly from the bath. Enough ferromanganese should be added to flux all of the solid suspended silica. Other scavenging agents are sometimes employed. With the heat of the desired composition and temperature and thoroughly deoxidized, it is tapped into the ladle, care being taken to ensure that the metal enters the ladle before any slag flows in.

Steel well made by the acid or basic electric process is probably as good as any that is made by any other method. In fact, it is difficult to say that steel made by one of the processes is inherently better than that made by the other, assuming both to be as well made as possible. The basic process is able to remove phosphorus and sulfur to very low values while, in the acid process, the purity with regard to these two elements depends entirely upon the purity of the charge and is usually less than the product of the basic furnace. Furthermore, the basic process is capable of more thorough deoxidation than the acid because the conditions at the end of the former process can be made really reducing while in the acid process there is a very small though positive value of FeO content beyond which deoxidation cannot go. For these reasons, basic electric steel is believed to be slightly better than the acid product if both are equally well made.

Induction Melting.—The high-frequency coreless induction furnace for the melting of alloy steel for small castings has gained considerable popularity in foundry work within the past decade. In this field, it has taken the place of the old crucible process because of the greater flexibility of operation, lower cost, rapidity of operation, and very close control of the analysis. At present, a furnace of 4 tons capacity is the largest that has been built while the average size for most work is between 1,000 and 2,000 lb. capacity. It is believed that the use of this type of furnace will increase when larger furnaces can be built.

The principle of operation of the furnace depends upon the fact that if a high-frequency alternating current of high voltage

is passed through a conducting coil, a secondary induced current of high amperage is set up in any metallic conductor that happens to be situated within the coil. The principle is that of a transformer. If the primary coil consists of a water-cooled copper coil and the secondary a heap of steel scrap, a high-frequency induction furnace is the result. The high current induced in the scrap heats it by its own electrical resistance, thus melting the charge. The essential parts of the furnace are shown in

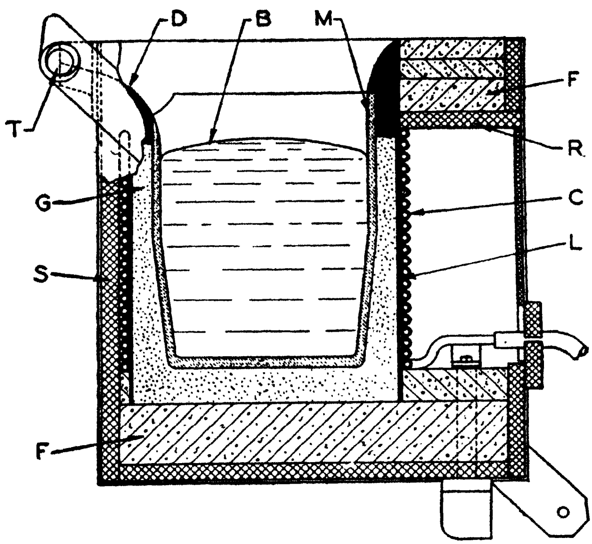


Fig. 3-XVII.—Cross-section of a high-frequency coreless induction furnace. (*Courtesy of the American Society for Metals.*)

cross section in Fig. 3-XVII. The outer shell S is made of asbestos lumber to which is attached the trunnions T on which the furnace pivots for tapping or pouring. The primary coil C is of water-cooled copper tubing and is lined with a layer L of refractory material to protect the coil from metal leaks if a breakout occurs. This layer extends both above and below the coil against the asbestos support R and the firebrick top and base F. The furnace lining usually consists of a crucible M which is packed in with pulverized refractory material G. This lining holds the metal charge B and is grooved out at one side of the top to form the pouring spout D.

Since the primary coil is quite close to the metal bath, the selection of refractories is very important. Most furnaces are built with basic linings, and MgO packing material and a crucible of the same material bonded with clay are often used. Sometimes an inner shell or crucible of asbestos board (Portland cement and asbestos fiber) is put in, which slags off on the first heat and bonds the inner layer of the magnesia packing. The life of the lining varies widely with the type of work but a record of 500 heats of stainless steel with a single lining has been reported. With ordinary practice, the life is considerably less than this.

The operation of this type of furnace has not been standardized as yet because of its newness but it is essentially a crucible process, no refining being attempted. The charge consists of carefully selected scrap and alloys so that the average analysis of the entire charge will be the same as the desired final analysis. If the entire charge can be packed into a crucible, no additions are made except for small amounts of final deoxidizers. Melting is rapid and only a slight loss of oxidizable elements occur. In most cases no attempt is made to use a slag blanket because it is not needed to prevent oxidation and because it is very difficult to keep the metal covered with a slag.

The heavy scrap is charged first, the furnace filled, and the current turned on. The induced current circulates in the charge in a direction opposite to but parallel with the current in the primary coil. This current is induced in the outer layers of the charge but the heat produced is conducted quite rapidly to the interior. As soon as a pool of molten metal starts to form, the charge sinks and any scrap that could not be crammed into the crucible at the start is now added. The current induced in the molten metal causes a rapid stirring action and helps in melting the rest of the charge by washing molten metal against the solid scrap. It also assures uniformity of mixing the charge and does away with the necessity of any manual stirring. As soon as the charge is completely melted, any necessary alloy additions and deoxidizers are added and the bath is superheated to the correct pouring temperature. The current is turned off and the heat poured by tilting the furnace. The entire operation for a 1,000-lb. charge does not usually consume much more than an hour.

The operation of the process is complicated somewhat if a slag blanket is used to attempt the partial removal of nonmetallics from the bath. Some operators believe, however, that the use of slags is worth the trouble because they seem to reduce the amount of nonmetallic inclusions present in the bath. There are two main disadvantages in the use of slags in induction melting. The first is that, owing to the rapid stirring action of the bath, it is difficult to keep a slag blanket over the metal as it tends to build up on the walls of the crucible unless a large amount is used. The other is that since the heat is generated in the metal and the slag is a nonconductor of electricity, the slag is heated only by conduction from the metal underneath. This causes the slag to be colder than the metal except at the interface, and in some cases the upper layer becomes solid. On the other hand, the continual agitation of the melt aids in bringing the nonmetallics to the slag-metal interface where they may be absorbed by the slag. A slag must be used whose melting point is below that of the metal.

In case refining slags are to be used, the charge in the furnace is sprinkled heavily with a mixture of 70 per cent lime and 30 per cent silica to minimize oxidation during melting. After the heat has become molten, the slag floats to the top and is composed of the slag mixture sprinkled on the charge, oxides resulting from the scale on the scrap and that due to oxidation during melting. This slag is skimmed off and more of the above mixture, to which is added a small amount of calcium silicide, is charged on the bath. The calcium silicide acts as a deoxidizer. The procedure of skimming off the slag and adding more to the bath is repeated until the skimmed slag fails to show any oxides of iron, manganese, etc., on fracture tests. Sometimes five or six additions and skimmings are necessary, after which the heat is poured.

Molding and Pouring Practice.—There are a few important differences between the problems confronting the cast-iron foundryman and those confronting the steel foundryman with regard to the properties of the two materials. In the first place, steel has a much higher melting point and, therefore, requires higher pouring temperatures as well as a mold that will stand these temperatures without fusing or losing its shape. In the

second place, steel shrinks more than twice as much as cast iron and more care is required in placing sinkheads, gates, etc., to prevent shrinkage cavities in the casting. Again, since steel is very liable to blowhole formation, great care must be taken in feeding the casting in order to prevent the trapping of gas in the mold. Above all, it should be remembered that a steel casting is really an ingot of more intricate shape and nearly all of the defects that occur in ingots may also be present in castings with the exception of those which are caused by the rigid walls of the ingot mold. In addition, steel castings often develop defects peculiar to themselves which require special methods in order to avoid them.

In the steel foundry, pattern molding is the most common method. In general, a pattern of the same size and shape as the desired casting is made of wood, placed in a much larger wooden or metal receptacle, called the *flask*, and tempered foundry sand tamped in between them. The pattern is then pulled out without destroying the shape of the cavity, and the mold is ready for use. In most cases, unfortunately, the procedure is not so simple, as the pattern is not shaped so that it can be removed and still leave the cavity intact. The flask is split into two or more parts, as in iron founding, the bottom being known as the *drag*, the intermediate portions as the *cheeks*, and the top as the *cope*. The pattern is cut into the same number of parts so that, when the sand is tamped around the assembly and the flask taken apart, the various parts of the pattern may be removed one at a time without destroying the shape of the cavity. The flask is then reassembled with the cavity in place to receive the metal. When holes through the casting are desired, or other depressions that cannot be made a part of the main mold, *cores* of baked sand are used.

Both *green-sand* (unbaked) and *dry-sand* molds (baked at 350 to 400°F.) are used in steel foundry work while skin-dried molds are used to some extent. Castings made in dry-sand molds have a better surface, are stronger, and are more likely to be sound (free from blowholes). On the other hand, green-sand molds have the advantage of being softer and more easily crushed by parts of the casting being drawn together due to shrinkage on cooling. If the sand does not give, the metal will crack. Green-sand molds require more careful venting to allow the steam to

escape. This is especially true of cores and they must also have a low crushing strength. With either type of mold, sand must be used that contains at least 90 per cent silica to ensure that it will not fuse. The bonding clay must also have a high melting point or the venting properties of the sand will be very low. More clay is necessary in dry-sand molding as the moisture in a green-sand mold helps to hold it together. The foregoing sketchy summary of mold making is included for review purposes only. A thorough discussion is given in Vol. I of this series in connection with Iron Founding, since the general method of making up molds is the same in both cases.

Three general classes of defects occur in steel castings against which the foundryman must guard:

1. Blowholes, sand holes, scabs, and other exterior defects.
2. Shrinkage cavities due to contraction of the steel—formed chiefly during solidification.
3. Stresses set up and cracks formed by contraction of the steel in the solid or semisolid state.

Before discussing the methods of eliminating or minimizing these defects in castings, it is only fair to say that the second and third classes are often due to the designer of the casting and not to the foundrymen. Engineers often design castings which, because of their shape, are practically impossible to cast and make sound or to prevent cracks from forming before they can be annealed. The precautions in design that are necessary to observe in designing castings will become evident from the following discussion of defects.

Blowholes in castings may be due to poorly degasified steel or improper venting of the mold. If the mold is made so that gases present in the sand cannot escape, they will enter the metal. This is particularly true of green-sand molds because of the water contained in them. Sand holes and scabs are caused by the flaking off of a certain amount of the mold due to wet spots, insufficient binder, and other causes. Any patches applied after withdrawing the pattern are apt to spall off during pouring. At points where the mold wall is apt to spall off for any cause, it is common practice to "nail" it in place, i.e., to stick large-headed nails into the sand every square inch or so to support the sand in place. The nails are shoved all the way in so that the heads are flush with the mold wall. Any slag incautiously

allowed to enter the mold from the ladle will cause surface defects as will sand washed loose by the stream, if it is trapped anywhere and cannot rise into the sinkhead.

Since steel castings solidify and cool in the same manner as ingots, some portion of the casting will always contain a shrinkage cavity. As in hot-top ingot practice, one or more sinkheads are provided at the top of the mold to feed the casting until it is entirely solid. It is obvious that the sinkhead or sinkheads must be of such a size and so placed that they will be the last to solidify and of ample size to feed the shrinking casting. Often the sinkhead takes the form of a simple extension of the upper end of the mold while in others a narrow neck must be provided and a larger sinkhead above it, if an extension of the top of the casting is too large or too small to serve the purpose. It is necessary that the neck be short because the small cross section may otherwise freeze and prevent the sinkhead from fulfilling its purpose. It is obvious that a perfectly designed sinkhead is useless if the rest of the mold is so placed that the metal will not freeze from the bottom up. This leads to the generalization that the lighter portions of a casting should be at the bottom and the heavier part just under the sinkhead. If such a mold design is not possible, *chills* are usually used. These are heavy pieces of iron or steel embedded in the sand at places where the molten metal, in coming in contact with them, will cool more rapidly than the portions not chilled. In this way a heavier section at the bottom may be made to cool faster than a lighter section above it. Also, cracking due to uneven cooling of sections of different size, especially at their juncture, may be prevented by chilling the heavier portion.

Another important factor in controlling the formation of shrinkage cavities and causing them to form in the sinkheads is the manner of pouring the casting. The ideal way is to pour the casting from the top so that the last, and therefore the hottest, metal will be in the sinkhead to feed the cooler portions of the casting. In most cases, however, this is not possible because the impact of the stream of metal cuts out the bottom of the mold and may also strike a core or otherwise injure the mold. Hence it is usually necessary to extend a vertical *runner* down the side of the mold with a *gate* at the bottom leading into the cavity in the mold at one side of the bottom. In this way, the

casting is formed from the bottom and the metal rises quietly in the mold without cutting the walls or splashing. This method has the disadvantage of having the first metal poured, and hence the coldest, at the top. It is the usual practice to pour the casting through the runner and then fill the sinkhead or sinkheads with hot metal direct from the ladle. This device works nicely if the casting is not too tall and the lighter portions are at the bottom but, if the top layer of metal has too far to rise, the fresh metal added to the sinkhead will not be sufficient to prevent bridging over somewhere below but close to the sinkhead. For tall castings, then, the method of pouring is known as pouring in sections or through multiple gates. A single runner at the side of the mold is used with several gates leading to the cavity, each succeeding one being placed above the next lower one. The metal is poured in through the runner and the cavity filled through the bottom gate until the metal reaches the level of the second gate. The metal then enters the mold through the second gate while the colder metal below does not rise farther but begins to solidify. In this way, a compromise between top and bottom pouring is reached without the dangers of ruining the mold through top pouring.

Cracks, the third class of defects, occur after solidification and while the casting is cooling to atmospheric temperature. The formation of cracks is favored by high sulfur and low carbon content in the steel, by uneven sizes of different parts of the casting, by sharp corners, and by resistance of the mold or cores to the shrinkage of the casting. High sulfur content causes the steel to be red short and very tender at high temperatures while low carbon steels shrink more than high carbon ones. If one part of the casting cools much faster than another, the cooler portion tends to shrink away from the hotter and, therefore, weaker portion, forming a crack between them. This condition is aggravated by having sharp corners where a thick and a thin section join because it serves as a focal point for the start of a crack. In fact, a sharp corner at any place in a steel casting is a potential source of weakness and it cannot be recommended too strongly to the casting designer that all corners should have large fillets. In this way, planes of weakness in the crystal structure extending in from the corner are eliminated, exactly as in ingots, and the dangers of cracking become very much less.

The method of getting the metal from the furnace into the mold depends upon the foundry and the size of the casting being poured. The metal is usually drawn from the furnace into a single ladle and, for small castings, transferred to small shank ladles from which the small castings are poured individually. The furnace ladles may be of the bottom-pour type, the lip-pour type, or the teapot type, each having advantages for certain types of work. In any event, it should be remembered that the metal should pour from the ladle free from slag. This is best accomplished with the bottom-pour and teapot types. The best pouring results are obtained by controlling the rate of pouring at all times. The pouring is generally started very rapidly and the rate gradually decreased as the mold fills. As soon as the metal has entirely solidified, it is advisable to break up all cores that can be reached to prevent cracks if the cores prove too strong for the shrinking metal surrounding them. If the casting is of intricate shape, it is often necessary to dig the mold away from it as soon as possible and charge it into a heated furnace where it is allowed to cool very slowly.

If the casting can be allowed to cool without danger of cracking, the sinkheads, gates, runners, nails, etc., are removed with a cutting torch or by breaking them off. Sandblasting is used to remove sand that cannot be scraped off easily, and fins or surface defects are ground off with portable grinding wheels. If the casting must be cooled in a pit, it is not thoroughly cleaned beforehand but only the sinkheads, gates, and nails are removed before further cooling.

The heat-treatment of castings has several purposes. In the first place, cooling strains are removed and all dangers of cracking when cold due to such stresses are avoided. Heat-treatment will also refine the grain structure of the casting and may also improve the physical properties. The most common heat-treatment for carbon steel castings is annealing, in which the casting is carried above its upper critical temperature and slowly cooled in the furnace. This treatment removes strains, reduces the grain size to a considerable extent, and tends to minimize segregation. In some cases, the treatment is repeated to refine the grain further and increase the strength and ductility, or the piece may be cooled in air the second time if its section is fairly uniform. The quenching and tempering treatments sometimes

given to castings to improve their physical properties cannot be considered here but will be covered in Vol. III.

Suggested Questions for Study and Class Discussion

1. Give the classification of steel foundries and the field of operation of each class.

2. Compare side-blown with bottom-blown acid Bessemer operation. What are the advantages of the side-blown vessel for foundry work?

3. Describe the making of a heat of carbon steel by the acid electric process. Give all necessary equations.

4. Discuss the induction melting process as applied to steel castings.

5. What are the general classes of defects found in steel castings? Give one method of eliminating or minimizing each.

6. Discuss the advantages of multiple gating for tall castings.

CHAPTER XVIII

SPECIFICATIONS

The word "specification" means something specific or definite in contrast with something general. Specifications are designed to promote uniformity of product and are indispensable in governing the manufacture of any product and the utilization of that product in the interests of uniformity. Specifications are controlled and governed by practical experience and doubt should never arise over the interpretation of any set of properly prepared specifications. The word "about" is never written into any specifications.

The specifications that approach closest to ideal are, probably, those drawn by large organizations having access to both theoretical and practical personnel. Thus, the specifications of the American Society for Testing Materials, covering practically every known commodity, are recognized as the criterion in the specification field. Specifications of the United States Steel Corporation and of the General Motors Corporation approximate, or are in some instances identical with, those of the American Society for Testing Materials, the only difference usually being in the limits set for the commodity, which limits have been found to meet the practical needs of the corporation.

Smaller corporations or plants usually follow the specifications laid down by larger concerns as being adequate to control the uniformity of product of their respective plants.

Specifications also are written to facilitate the purchase of materials in order that those materials may fit accurately into a manufacturing scheme. They should be so worded that both the vendor and the customer have an accurate word picture of the application of the material. To meet this requirement the customer organization should be equipped with a personnel trained in the accurate expression of the requirements of the product to meet the job for which the specification is written. The vendor should have an equally trained staff capable of interpreting

exactly the requirements specified. He should carefully avoid any substitutions and his contact with the customer should be honest, conscientious, and scrupulous.

Any specifications worthy of writing should clearly cover all requirements and effectively close all loopholes. The following are some of the essential points to be covered in a specification for steel:

1. *Description.*—State the kind, how made, and the operation to which the steel will be subjected.
2. *Kind.*—Give the dimensions of the piece.
3. *Accuracies.*—Correct, maximum, and minimum dimensions.
4. *Finish.*—List the surface requirements and the defects not permitted.
5. *Chemical Properties.*—State all the chemical properties desired and give the tolerances allowed.
6. *Physical Properties.*—State the desired physical properties and give the tolerances allowed.
7. *Chemical Inspection.*—State how sampling will be done for chemical analysis.
8. *Physical Inspection.*—State the method of sampling for the physical inspection. Give the kind of gauges and tools used in testing.
9. *Other Instructions.*—Here give other necessary data pertaining to wrapping, coiling, and surface protection.
10. *General.*—Here specify the method of acceptance or rejection. Also retain the right to inspect the steel at the mill.

It should be remembered that the more severe the specification, the higher the price the customer has to pay for the product. Therefore, specifications, although they should be binding, should not unnecessarily carry terms outside the scope of the requirements of the material they are designed to protect.

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